

Criticality Safety Study of the Subsurface Disposal Area for Operable Unit 7-13/14

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March 2002*



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Environmental Restoration Program
Idaho Falls, Idaho 83415**

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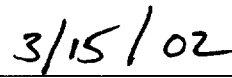
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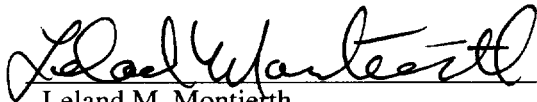


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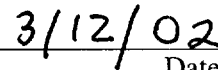


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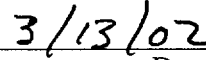
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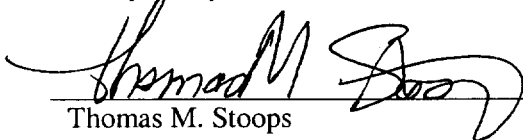
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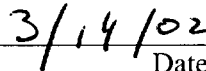
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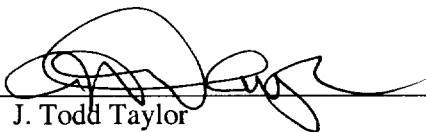
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ABSTRACT

The primary purpose of this document is to address the potential for a criticality in the Subsurface Disposal Area (SDA) by evaluating postulated configurations of specific waste matrices determined by engineering judgment to be of greatest concern. A criticality safety study was performed in FY 2001 to address issues relating to postulated criticality scenarios in the SDA for Operable Unit 7-13/14 in the Radioactive Waste Management Complex at the Idaho National Engineering and Environmental Laboratory. The study was designed to demonstrate the sensitivity of critical configurations to the various parameters affecting critical systems.

Based on the results of this study, a criticality is not credible with the expected fissile masses and waste forms in the SDA. However, the frequency cannot be said to be zero because enough fissile mass exists as buried waste in the SDA to achieve criticality, though not in a form and distribution that lends itself to criticality in a reasonable or feasible manner.

EXECUTIVE SUMMARY

The primary purpose of this document is to address the potential for a criticality in the Subsurface Disposal Area (SDA) by evaluating postulated configurations of specific waste matrices determined by engineering judgment to be of greatest concern. A criticality safety study was performed in FY 2001 to address issues relating to postulated criticality scenarios in the SDA for Operable Unit 7-13/14 in the Radioactive Waste Management Complex at the Idaho National Engineering and Environmental Laboratory. The study was designed to demonstrate the sensitivity of critical configurations to the various parameters affecting critical systems.

As shown by the study, a postulated criticality safety assessment of the SDA is dependent on known factors that affect criticality. These factors include the amount of fissile mass and moderator present, geometrical configurations, the presence of diluents or neutronic poisons, reflection conditions surrounding the fissile systems, and the concentration or distribution of the fissile material in the waste. Most of these factors would have to be optimized in some combination to achieve a critical system. As deviations from optimum conditions occur, the reactivity of the systems decreases dramatically.

Models were developed that evaluated three individual types of waste matrices: high-efficiency particulate air (HEPA) filters, graphite, and MgO. The HEPA-filter matrix was chosen because overloaded waste drums containing this waste matrix have been discovered in the aboveground storage operations. In addition, HEPA filters historically have higher fissile loading. Graphite was chosen based on historical data indicating the possibility of high fissile loading in this waste matrix and the moderation properties of graphite. Magnesium oxide also was chosen because overloaded waste drums containing this waste matrix have been discovered in the aboveground storage operations. The effects of varying each of the factors affecting criticality discussed above were evaluated in each of the models. This was done in an attempt to quantify the reactivity effect as the various factors were permuted. Once the effects are understood, an analysis can be made for how these permutations could be related to expected real-world configurations.

The effect of having fissile mass present is rather straightforward and well understood. The more mass present (in general), the more reactive the system becomes. When a moderator is introduced into the system in near-optimum amounts, less fissile mass is required to postulate a critical configuration. Models were developed to evaluate the effects of the exclusion of water in each of the three waste matrices. In addition, a set of models consisting of filter arrays loaded with lower, more realistic fissile material loading was evaluated to show the effects of fissile mass in that specific configuration.

The effects of geometry on the fissile systems were evaluated in various model permutations. Models were evaluated where the filters were separated by different amounts of soil to determine the effects of spacing on reactivity. As expected, when spacing increases, the reactivity of the system decreases. The effects of homogeneity versus heterogeneity were evaluated in models involving both filters and graphite waste types. As expected, when the fissile material

distribution becomes less optimized and less homogeneous, the reactivity of the system decreases.

The effects of various neutronic poisons and diluents were evaluated in different models. In one case, the effects were evaluated for boron being present in the soil and becoming soluble thus intermixing with the fissile material and the filter. In another case, the effects of soil intermixing with the fissile material in the filter were evaluated. As expected, when the moderator was excluded in the filter structure, as a result of soil presence, the reactivity of the system decreased. The effects of boron in the native soil in the SDA were somewhat limited because of the small fraction of resident boron.

Reflection was evaluated by modeling a case in which the filter and fissile material system were both near optimum moderation with the soil surrounding the system being void of water. The lack of water in the reflecting layer increased the neutron leakage away from the fissile system. When compared with a similar fissile system containing a fully saturated soil reflector, the reactivity of the system lacking water in the reflector yielded a much lower calculated effective multiplication factor.

The concentration or distribution of the fissile material is another parameter that affects the reactivity of a particular system. As expected, the study showed that as the fissile material is diluted over a large volume at low concentration, the reactivity of the system decreases to a point where a critical system is not possible. However, if the fissile material is distributed at relatively optimum concentrations, higher system reactivity is achieved.

Based on the results of the study, a criticality is not credible in the SDA with the expected fissile masses and waste forms. However, the frequency cannot be said to be zero because enough fissile mass exists as buried waste in the SDA to achieve criticality, though not in a form and distribution that lends itself to criticality in a reasonable or feasible manner.

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ACRONYMS

HEPA	high-efficiency particulate air filter
INEEL	Idaho National Engineering and Environmental Laboratory
k_{eff}	effective multiplication factor
RFP	Rocky Flats Plant
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area
wvf	water volume fraction

Criticality Safety Study of the Subsurface Disposal Area for Operable Unit 7-13/14

1. INTRODUCTION

1.1 Purpose

The primary purpose of this report is to address the potential for a criticality in the Subsurface Disposal Area (SDA) by evaluating postulated configurations of specific waste matrices, determined by engineering judgment to be of greatest concern.

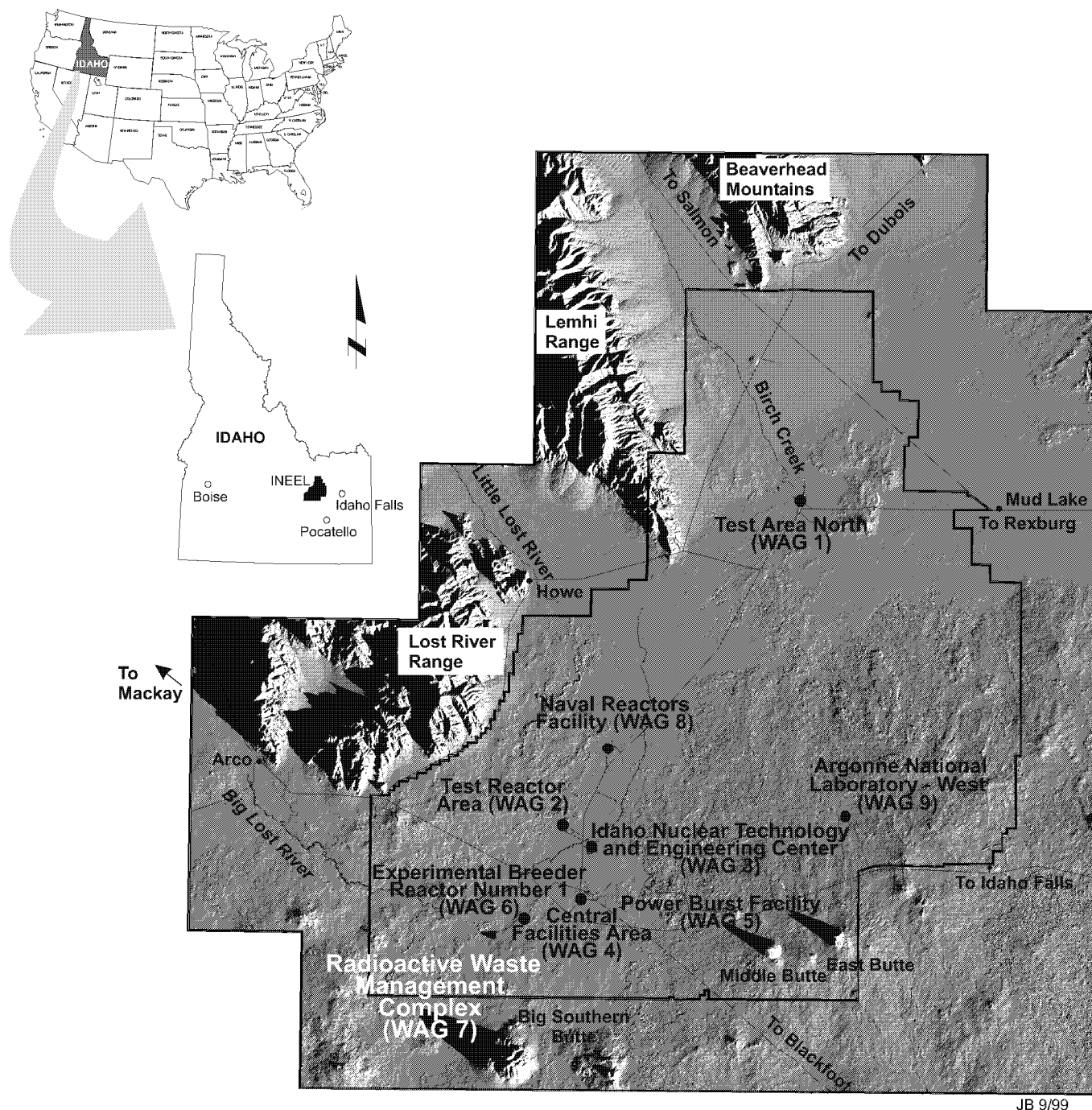
A criticality safety study was performed in 2001 of the SDA, which is located in the in the Radioactive Waste Management Complex (RWMC) at the Idaho National Engineering and Environmental Laboratory (INEEL), to support the Operable Unit 7-13/14 comprehensive remedial investigation/feasibility study required by Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) for Waste Area Group 7. Waste Area Group 7 is the designation recognized under the Federal Facility Agreement and Consent Order (DOE-ID-1991) and CERCLA for the RWMC. A map of the location of the RWMC at the INEEL is provided in Figure 1.

The study was performed address issues relating to postulated criticality scenarios in the SDA. The study was designed to demonstrate the sensitivity of critical configurations to the various parameters affecting critical systems. Specifically, this criticality safety study was performed to determine postulated configurations and the related calculated effective multiplication factors (k_{eff}) of fissile material buried in the SDA. The configurations evaluated in this report are based on different factors including conservative estimates, best available data, and engineering judgment. The lack of specific historical data relating to configurations and distribution of fissile material in the SDA leads to some of the conservative assumptions and engineering judgment used in this report.

The parameters affecting criticality in a fissile system include (1) the mass of fissile material present, (2) the presence of moderating material, (3) the geometric configuration, (4) the presence of diluents and neutronic poison material, (5) the reflection conditions around the system, and (6) the concentration and distribution of the fissile material in the waste. Each of these parameters and the effects they have on reactivity will be evaluated in later computational models. Appendix A contains spreadsheets showing the mathematical calculations that produced the input parameters used in the computational models. Appendix B shows in tabular form the soil composition and input parameters that were used in the computational models.

The three waste forms containing fissile material that were evaluated in this study include high-efficiency particulate air (HEPA) filters, graphite, and MgO. These three waste forms were chosen for different reasons. The HEPA filters were chosen because overloaded waste drums containing this waste matrix have been discovered in the aboveground storage operations. In addition, HEPA filters historically have higher fissile loading. Graphite was chosen based on historical data indicating the possibility of high fissile loading in this waste matrix and the moderation properties of graphite. Graphite is a good neutronic moderating material in large systems that consist of somewhat homogeneous distributions of fissile material. Magnesium oxide also was chosen because overloaded waste drums containing this waste matrix have been discovered in the aboveground storage operations.

Sludge was not considered because of the forms of the sludge and the historically low fissile loading in the sludge matrices. Most of the sludge matrices contain a large amount of CCl_4 , which is a very good neutronic poison. Chlorine is an excellent neutron absorber that effectively lowers the



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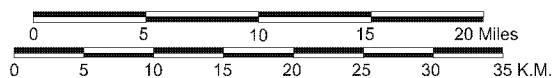


Figure 1. Map of the Idaho National Engineering and Environmental Laboratory showing the location of the Radioactive Waste Management Complex and other major facilities.

reactivity of the system by removing neutrons. In addition, sludges inherently prohibit the optimum conditions required for the formation of a critical system.

Several concurrent parameters must exist for a critical configuration to occur. For example, enough fissile mass must be present in the system. In an optimally moderated and near-optimally configured fully reflected system, the fissile mass necessary to achieve a critical system is on the order of 520 g (18.3 oz) of Pu-239 and water. The mass significantly increases for a dry system consisting of PuO₂. Moderating material must be present in sufficient quantities or the mass necessary to achieve a critical system will exceed the localized fissile mass expected in the SDA. In addition, the geometrical configuration must be near the optimum state. The fissile material must be distributed in a matrix lacking diluents that act as neutronic poisons. Lack of moderating material or the presence of diluents increases the mass needed to achieve a critical system.

The distribution or concentration of the fissile material in the waste buried at the SDA is not well quantified. If the waste were packaged in accordance with the established limits, then the waste forms would remain subcritical even under fully moderated conditions. No postulated mechanisms exist to preferentially concentrate plutonium in the SDA. In addition, the likelihood of multiple overloaded drums being placed in adjacent positions in the SDA is very low. Under realistic conditions, achieving a critical system would be very difficult even in a grossly overloaded drum. Waste packages composed of wood or cardboard are known, from past retrieval operations, to have little to no structural integrity, thus precluding the accumulation of moderator.

Subsidence events at the SDA lend additional data that the buried waste containers and waste forms at the facility are being compressed by the overburden because of the degradation occurring in the buried waste. The degradation of the waste packages leads to the intermixing of soils more intimately with the waste forms and fissile material, thus increasing the mass necessary to achieve a critical system.

In addition, probing operations in which Lexan tubes were placed into the various waste matrices indicate degradation of the waste drums that housed the buried waste. As in the case of the wooden and cardboard boxes, when the drums physically degrade, soil will be intermixed into the waste matrices with the fissile material.

The calculated k_{eff} s associated with the postulated configurations were determined in this study. In addition, the reactivity effects are demonstrated between conservative model configurations and the expected actual realistic configurations in the waste buried in the SDA.

No criticality concerns would exist if the buried waste complied with the 200-g (7-oz) limit of fissile material per drum and the box limit of less than 5 g (0.17 oz) of fissile material per cubic foot with a total gram loading not to exceed 350 g (12 oz) per box. However, assay data indicate drums have been overloaded in the past (Woods and Neeley 2001).

By using computational methodology, incorporating conservatism into model systems that yield very reactive calculated k_{eff} s is easy, especially in cases consisting of buried waste forms containing fissile material. These models are generally very ordered in nature and represent configurations that would not be expected in the waste forms. As stated previously, any derivation from these ordered systems and the reactivity readily decreases. Various configurations will be evaluated to demonstrate the effects of the parameters previously outlined.

In short, a criticality is not credible in the SDA with the expected fissile masses and waste forms. The frequency cannot be said to be zero because enough fissile mass exists as buried waste in the SDA to

achieve criticality, though not in a form and distribution that lends itself to criticality in a reasonable or feasible manner.

A flow diagram of the logic used in this report is shown in Figure 2. This figure is a pictorial representation of the methodology and logic used to determine k_{eff} s for the selected waste matrices in the postulated configurations. Appropriate sections and the associated tables outlining model descriptions and results are identified on the flowchart to aid in understanding the logic used in this analysis. As identified in the flowchart and demonstrated in the computational modeling, all of the evaluated base-case configurations remained subcritical.

Flowchart of the Criticality Safety Study of the Subsurface Disposal Area for Operable Unit 7-13/14

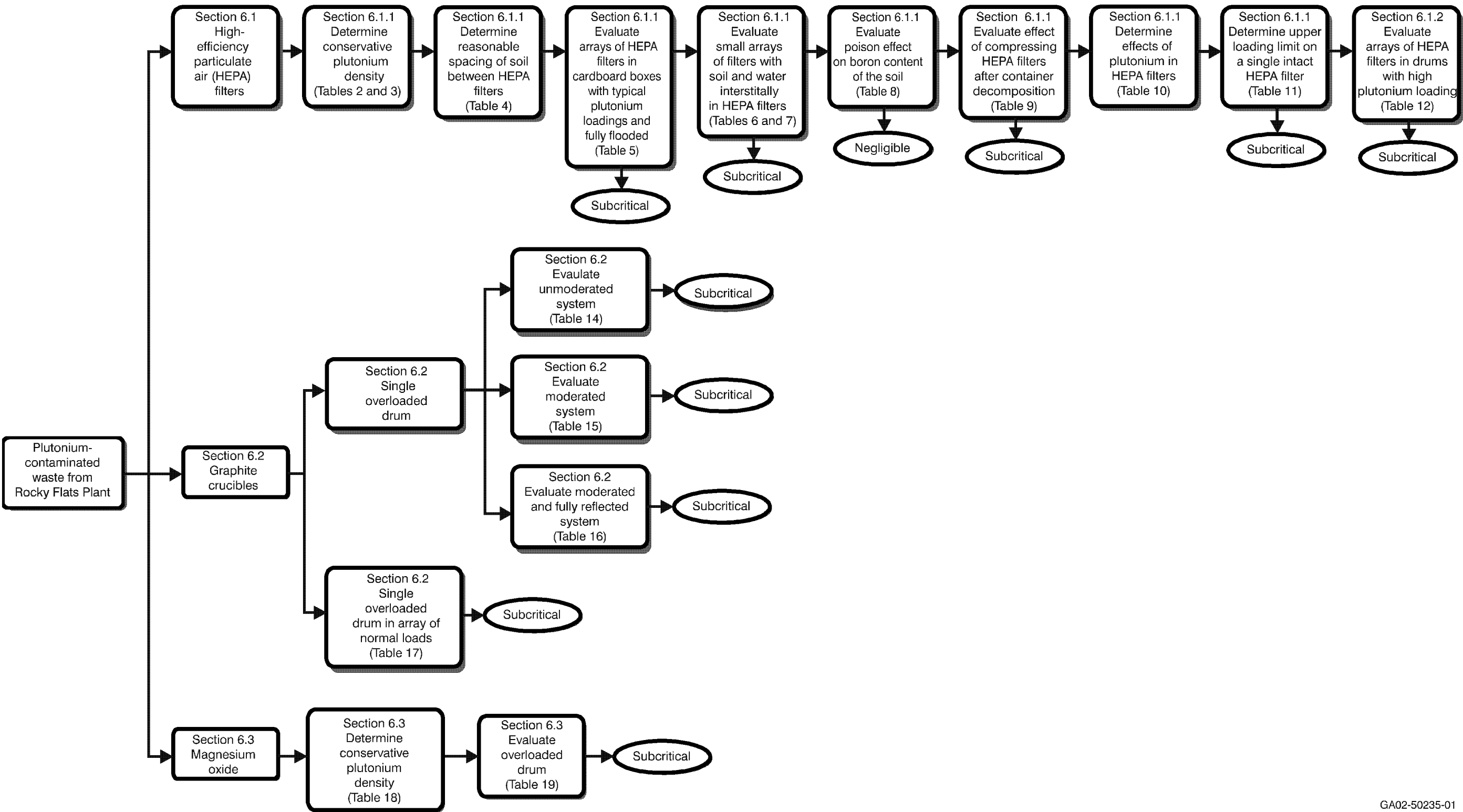


Figure 2. Flow chart of the criticality safety study for the Subsurface Disposal Area.

2. BACKGROUND

The SDA is a 96.8-acre (39.2-ha) tract of land, as shown in Figure 3, located in the western portion of the RWMC at the INEEL on the Snake River Plain of southeastern Idaho (see Figure 1). The SDA is used to dispose of radioactive waste material in underground pits, trenches, soil vault rows, and similar structures. The SDA contains drums and waste boxes of plutonium-contaminated waste from the Rocky Flats Plant (RFP).^a The thickness of the overburden is 0.9 to 1.8 m (3 to 6 ft). The trenches are approximately 2 m (7 ft) wide, 275 m (902 ft) long, and an average of 4 m (13 ft) deep. The pits are 30 m (98 ft) wide, 4 to 10 m (13 to 33 ft) deep, and vary in length from 60 to 360 m (197 to 1,181 ft).

Most of the waste contained in the SDA was received from RFP. Because of the mission of the RFP, the waste consists of plutonium-contaminated material. Three waste matrices were identified from the various identified waste streams received from RFP as possible problem areas in the SDA based on limited historical assaying data and engineering judgment. These three waste matrices include glovebox high-efficiency particulate air (HEPA) filters, graphite, and MgO.

The first type of waste matrix evaluated was the HEPA filters. Various sized HEPA filters were used in different capacities over the RFP operating history. Historical data^b indicate that the first- and second-stage glovebox HEPA filters had a higher fissile loading than those used in the final-stage building air outlet plenums. This makes sense because the purpose of a filter is to remove particulate matter from a system. The geometrical configuration of the filters and the higher fissile loading that could be present make this waste matrix a logical choice for evaluation. Therefore, the greater the number of filters in-line, the less accumulation would be expected on the final-stage filters. The first- and second-stage filters were smaller filters that were housed near the process gloveboxes. The first-stage filters were located at the air outlet from the glovebox and the second stage filters were located not far down the ventilation line. A more detailed description is contained in the sections pertaining to the models developed for these filters. The filters are of concern because some of the filters are known to have high fissile content estimated to be on the order of 200 g (7 oz) of plutonium in a single first-stage filter. The nature of the HEPA filters would give a rather ordered array of layers of plutonium deposited on the filter media. If moderated by water, a large number of filters in an ordered array could yield calculated k_{eff} s that are high. Various configurations and arrays containing different constituents were analyzed. The results from these cases and a description of the configurations can be found in the evaluation and results section in this report.

The second type of waste matrix evaluated was plutonium intermixed with graphite. Graphite is also a byproduct from past production operations at RFP. This waste matrix was chosen because known overloading of these types of drums has occurred at RFP in the past (see footnote b). In addition, graphite is known for its moderation properties, which make this type of waste a logical candidate for investigation. Critical systems comprising fissile material and graphite generally are known to be very large in size with large graphite and fissile masses.

The third type of waste matrix evaluated was plutonium intermixed with MgO. Magnesium oxide is a byproduct of production lines that were in use at the RFP site. Currently, in the aboveground drum

a. Rocky Flats Plant, located 26 km (16 mi) northwest of Denver was renamed the Rocky Flats Plant Environmental Technology Site in the mid-1990s. In the late 1990s it was again renamed, to the Rocky Flats Plant Closure Project.

b. D. E. Kudera, Interdepartmental Communication to W. H. Sullivan, March 28, 1994, "Historical Rocky Flats Plant Information on Plutonium Losses to Burial," DEK-04-94, Idaho National Engineering and Environmental Laboratory, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.

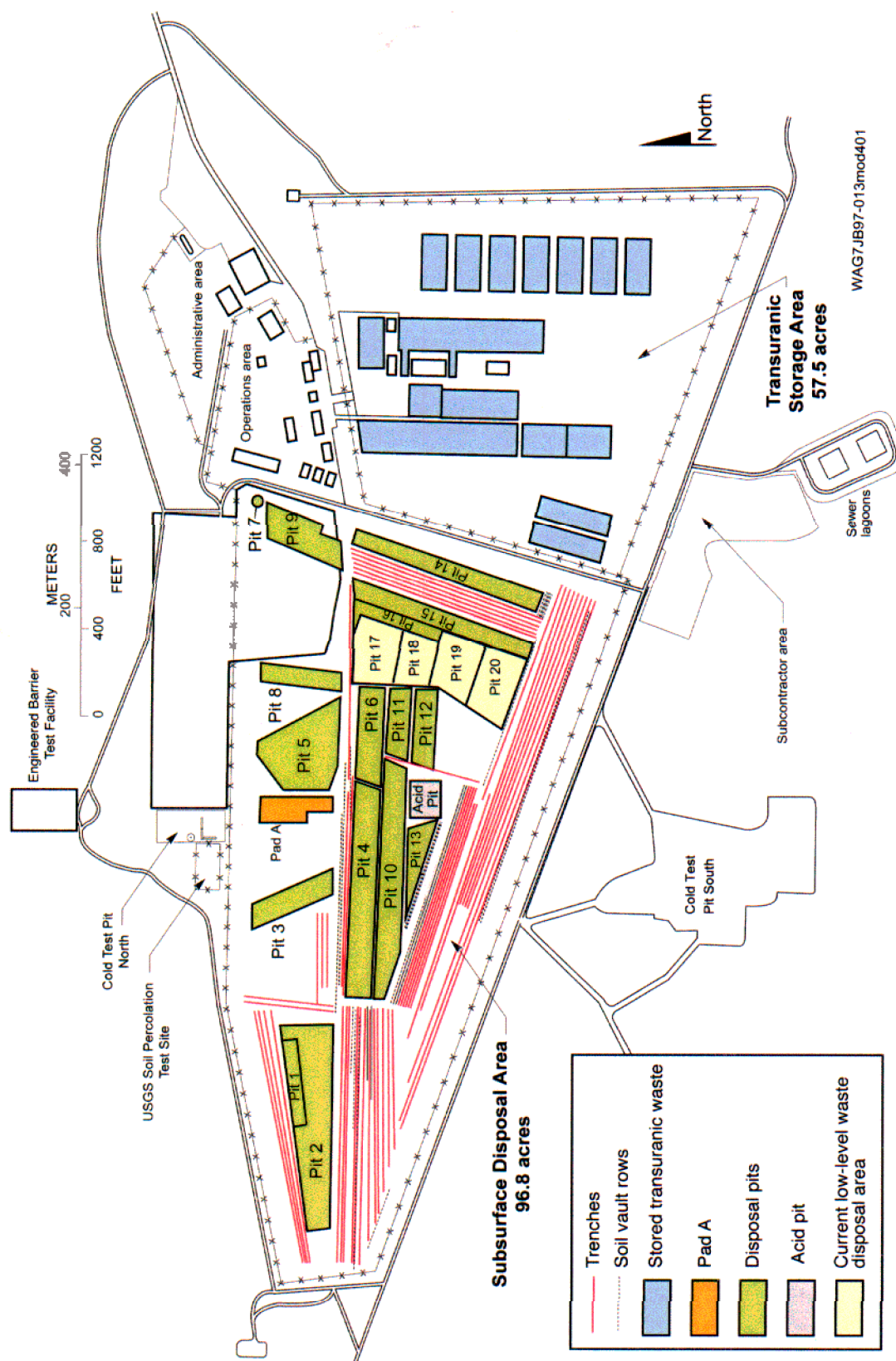


Figure 3. Subsurface Disposal Area at the Radioactive Waste Management Complex showing pits, trenches, and soil vault rows.

storage facility, eight drums of MgO waste are classified as overloaded (Woods and Neeley 2001). These drums exceed the prescribed drum fissile-loading limit allowed for disposal at the RWMC. The highest-loaded MgO waste-matrix drum currently in storage contains an estimated 1,360 g (48 oz) of plutonium. The calculated k_{eff} was evaluated for various configurations comprising MgO and plutonium in the SDA. These calculations helped determine the relationship between loading, configuration, and other parameters that affect reactivity.

Any plutonium metal, other than large pieces, will have undergone oxidation so that its form will be PuO_2 . A large single piece of metal or a small grouping of larger pieces of metal with a fissile material loading in the range of the expected mass is not a criticality issue because the heterogeneous distribution of plutonium would lead to a system with a lower reactivity than the homogeneous models that were evaluated. Therefore, the plutonium was modeled as PuO_2 in all of the cases. The PuO_2 was modeled with a plutonium isotopic composition of 95% Pu-239 and 5% Pu-240. This isotopic distribution envelops the isotopic distribution of weapons-grade plutonium that could be in RFP waste.

The modeling composition of the soil used in the various cases (Callow et al. 1991) is listed in Appendix B (see Table B-1). Variations in the soil density and water content were evaluated for these configurations.

3. REQUIREMENTS DOCUMENTATION

This is a criticality safety study and will not be used to set operational limits; therefore, no unique requirements apply at this time.

4. METHODOLOGY

All calculations listed in this report were performed using MCNP-4b2 (see Appendix C) with the ENDF/B-V (RSIC 1997) point-wise continuous energy neutronic cross-section library. The computational platform consisted of Hewlett-Packard workstations using the HP-UX 10.20 operating system.

Because criticality limits are not being developed for implementation by this study, comprehensive validation work will not be comprehensively addressed in this study. The makeup and compositions evaluated in this study are very different from the vast majority of critical experimental data currently available in the open-published literature. However, some critical experiments exist that can validate individual components of the waste matrices and the computational methodology used.

A set of critical experiments involving SiO₂, polyethylene, and highly enriched plutonium was conducted at the Institute of Physics and Power Engineering, in Obninsk, Russia, at the Big Physical Stand. This set of critical experiments covered a wide range of neutron spectra with fission ranging from thermal to intermediate. The systems composing the critical assembly consisted of plutonium metal ingots, SiO₂ discs, and polyethylene discs that were placed into sets of aluminum tubes. These tubes then were arranged to form a critical configuration. A full description of these experiments can be found in the International Handbook of Evaluated Criticality Safety Benchmark Experiments (OECD 2001). Computational verification of the critical configuration is included as part of this effort. The computational methodology used was MCNP-4b2, with the same continuous energy cross sections as used in this study. The computational methodology and critical experiment exhibited good agreement. The agreement indicates that for the SiO₂ and plutonium systems modeled in this study, the calculated keff would be similar to the actual keff if the configuration existed in the SDA.

This study shows that the most reactive configurations exist with the postulated scenarios of intact water-flooded glovebox HEPA filters arranged in an ordered array. Critical experiments that involve plutonium and nitrate solution systems are described in the International Handbook of Evaluated Criticality Safety Benchmark Experiments (OECD 2001).

Most of these critical systems comprise PuNO₃ mixtures in either spherical configurations, both unreflected and reflected, or an array of cylinders containing PuNO₃ solution. Computational verification of the critical configuration is included as part of this effort. The MCNP-4b2 computational methodology was used with the same continuous energy cross sections as used in this study. The computational methodology and critical experiment exhibited good agreement. The agreement indicated that for the water-flooded filter and plutonium systems modeled in this study the calculated keff would be similar to the actual keff if the configuration existed in the SDA.

Very little validation work relating to MgO is available. A further review of other sources of applicable validation work would be necessary to adequately validate the MgO and plutonium in a mixed system.

The scarcity of validation work is similar for the actual systems that consist of plutonium dispersed in graphite. Limited validation work is available for a metal plutonium sphere surrounded by a graphite reflector. This validation work would provide some level of confidence to ensure that the graphite cross sections are being treated properly for the intended application.

A comprehensive validation section in this study is not currently a requirement because the purpose of this study is to investigate the various parameters present in the SDA and how they affect reactivity. If this study were used in the future to support actual operations, a more comprehensive validation section would be required.

5. DISCUSSION OF CONTINGENCIES

This study does not pertain to a current or proposed operation in the sense that normal fissile operations are generally evaluated and controlled. As previously stated, the study was designed to demonstrate the sensitivity of critical configurations to the various parameters that affect critical systems.

The waste in the SDA is buried and for the most part has been buried for more than 30 years. Before being shipped from RFP, the fissile mass of a single container was limited to 200 g (7 oz) of plutonium in the case of drums and 350 g (12 oz) of plutonium in the case of large wooden storage boxes. Whether these limits were adhered to in past operations, when waste drums were loaded at the waste-generating location, has come under question because of the overloaded-drum issues in the aboveground storage area of the RWMC. However, because plutonium is a valuable commodity, efforts were made at RFP to recover as much as possible from the waste material before shipment for disposal. Consequently, even though the assaying methods used by RFP to determine whether the fissile-material limits for shipment to the INEEL were adhered to were not as advanced as current assaying methods, a concerted effort existed to recover as much plutonium as possible from process waste. Therefore, this analysis does not delineate specific controls and contingencies that need to be implemented and followed to ensure that an unplanned criticality event does not take place.

However, this analysis shows that to achieve a critical system with a reasonable amount of fissile material, water must be present and intermixed with the fissile material in a near-optimum ratio of moderator to fissile material. Therefore, the exclusion of water from the system would preclude a critical system from forming in the SDA.

6. EVALUATION AND RESULTS

As mentioned previously, three waste matrices were evaluated in combination with PuO_2 and various other parameters to determine the calculated k_{eff} for the postulated configurations. These three waste matrices (i.e., filters, graphite, and MgO) are discussed in detail in the following sections.

6.1 High-Efficiency Particulate Air Filters

6.1.1 Filter Arrays in Soil

Various sized HEPA filters were used at a number of facilities in support of several operational lines. The types of HEPA filters of concern came from the pre-1970 timeframe. These HEPA filters, also known as chemical warfare service filters, were constructed of either a wood or steel frame with a cellulose (i.e., paper) filter media. The filter media were impregnated with asbestos for fire retardation purposes. In the 1970s, the cellulose filter media were replaced by a glass-type filter media. A review of historical data indicates that no drums containing this glass-type filter media have been buried in the SDA; therefore, this study was restricted to the cellulose type of HEPA filter.^c

The specifications for HEPA filters for the pre-1970 timeframe are delineated in military specifications MIL-F-51068C (Military Specification 1970), MIL-F-51079A (Military Specification 1970), and MIL-F-51079C (Military Specification 1980). The filter dimension specifications are listed in Table 1.

Table 1. Dimensions of high-efficiency particulate air filters.

Filter Type	Dimensions (in.)		
	x	y	z
1	8 (+0, -1/16)	8 (+0, -1/16)	3 1/16 (+1/16, -0)
2	8 (+0, -1/16)	8 (+0, -1/16)	5-7/8 (+1/16, -0)
3	12 (+0, -1/16)	12 (+0, -1/16)	5-7/8 (+1/16, -0)
4	24 (+0, -1/8)	24 (+0, -1/8)	5-7/8 (+1/16, -0)
5	24 (+0, -1/8)	24 (+0, -1/8)	11 1/2 (+1/16, -0)
6	24 (+0, -1/8)	24 (+0, -1/8)	11 1/2 (+1/16, -0)

The smaller filters (Types 2 and 3) were used as the pre-filters or first- and second- stage filters at RFP. The larger filters (Types 4, 5, and 6) were used as the plenum filters and received much less fissile material accumulation. The filter media were housed in a plywood frame 1.9-cm (3/4-in.) thick with aluminum separator plates in the filter itself. The filtering medium was constructed as a single continuous sheet that was wound around a series of 0.48-cm (3/16-in.) mandrels. The filter media specifications included a minimum thickness of 0.038 cm (0.015 in.) with a maximum thickness of 0.0102 cm (0.040 in.). Schematics of the filter are shown in Figures 4 and 5 (LMITCO 1998).

c. Paul J. Sentieri, personal conversation with Bruce H. Becker, May 2000, Idaho National Engineering and Environmental Laboratory, Bechtel BWXT Idaho, LLC.

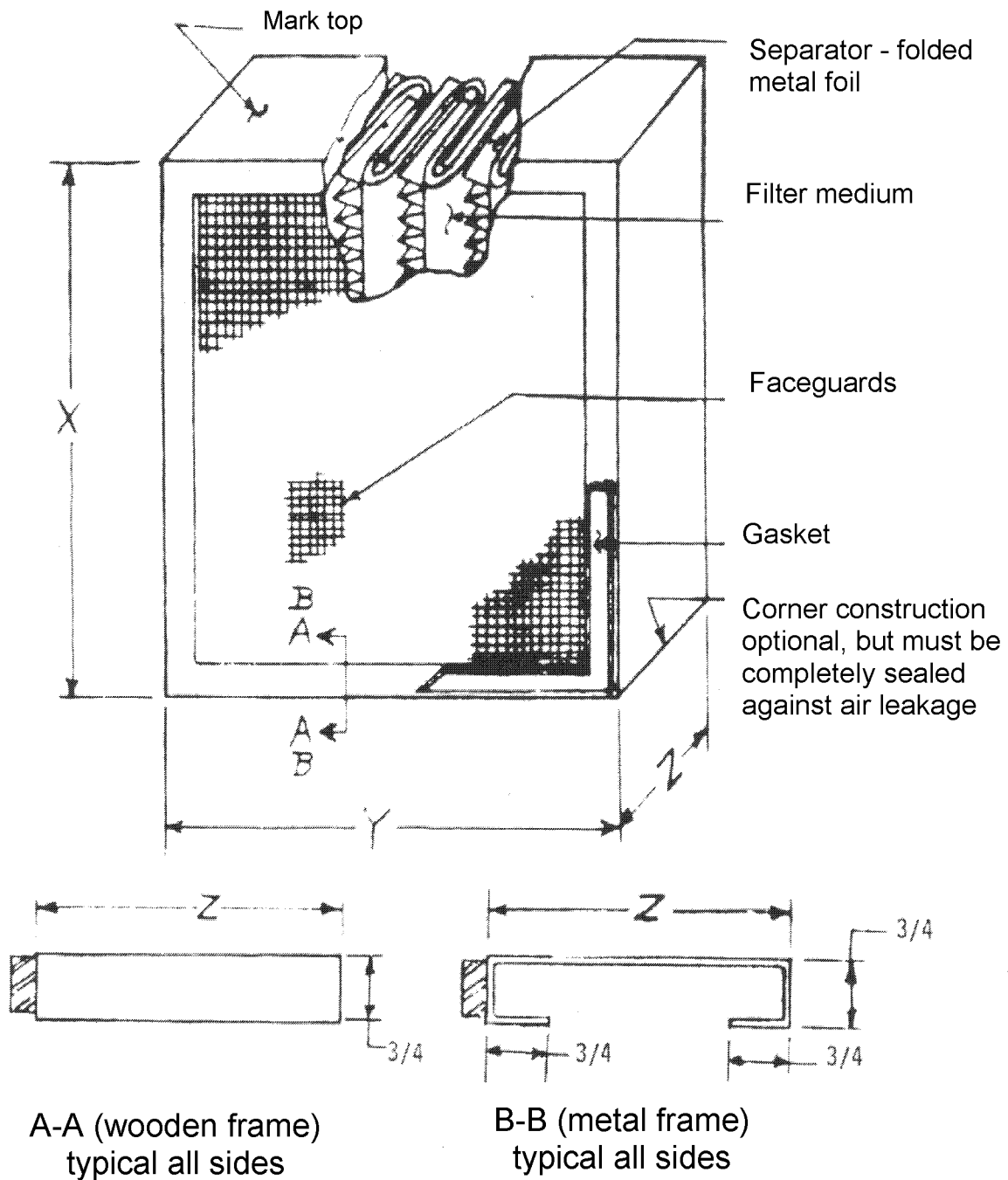


Figure 4. Sketch of a high-efficiency particulate air filter.

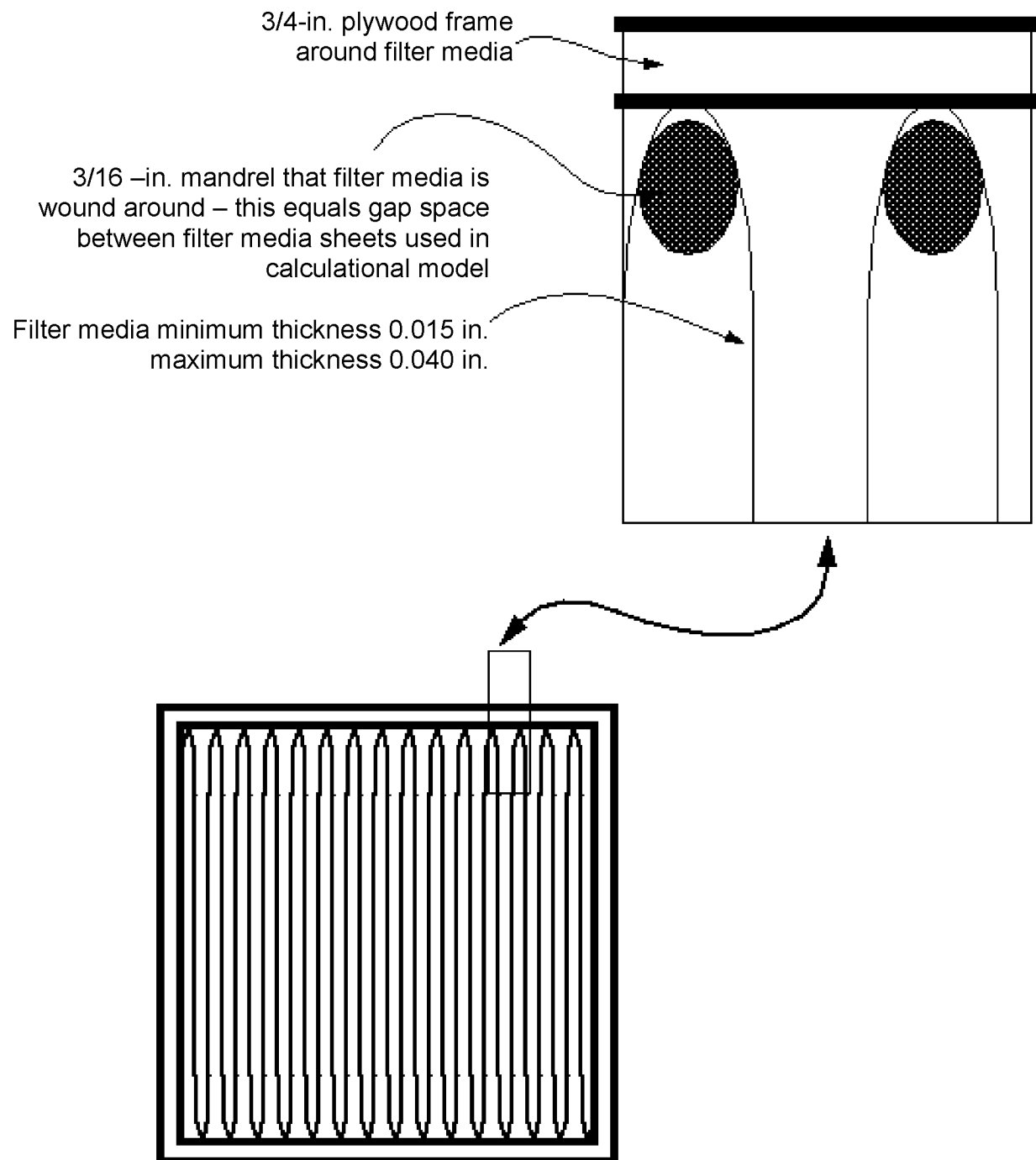


Figure 5. Schematic of the high-efficiency particulate air filter configuration.

For this study, the aluminum spacers were ignored in the filter models. Aluminum has a low neutronic absorption cross section and would have a negligible effect on reactivity. The presence of the aluminum spacers would help the filters maintain structural integrity along with the wood frames; however, they would also preclude water, thus making it conservative to leave them out of the calculational model.

Past retrieval efforts have occurred in the SDA (Thompson 1972). A retrieval effort was undertaken in the early 1970s and documented in an attempt to quantify plutonium migration in pits in the SDA and the condition of waste storage containers including drums, cardboard boxes, and wooden boxes. At the time of this retrieval effort, which took place more than 30 years ago, the waste had been emplaced for approximately 15 years. At the time of this retrieval effort, Thompson (1972) noted that some of the waste drums were in excellent condition while others had corroded through. Thompson also stated that it was apparent that damage to the barrels during the dumping operations was extensive and had resulted in many open barrels. Plywood boxes and cardboard cartons were deteriorated to the extent that they had no containment value. Thompson also documented the results of samples taken in the waste matrix to determine plutonium migration: very limited, if any, migration of the plutonium had occurred. These data support the conclusion that the waste matrix material is probably intermixed with soil in a disordered configuration, most likely in the case of the cardboard cartons and wooden boxes. In addition, the HEPA filters were constructed of cellulose material similar to the cardboard cartons that had deteriorated. This similar construction supports the argument that the filter media and wooden frames likely also have deteriorated.

The filters for this study were assumed to be intact and were modeled as such to evaluate the upper-bound reactivity that could be achieved in an ordered array with the plutonium dispersed in a homogeneous manner among the filters, which is extremely conservative.

In the first series of cases, an array of filters in soil was considered. Past RFP practices for shipping included shipping-used HEPA filters in cardboard boxes. No conclusive data readily can be found to indicate that only the large, lower-loaded HEPA filters were shipped in this fashion. Therefore, for this study, an array of first- and second-stage filters was assumed to have been shipped in cardboard containers that had degraded. Therefore, the filters were modeled in various arrangements in soil. In addition, early placement of the waste into the SDA was done in an orderly fashion to preserve space. In the case of square boxes, drums, and large wooden boxes, an orderly stack was assembled in the waste array. However, high radiation exposures to workers led to the abandonment of this practice in the late 1960s. Once again, no conclusive, readily available data exist to refute that these filters were not placed into the SDA in a stacked orderly fashion. If the filters were housed in cardboard boxes and were constructed with a wooden frame, then a good argument can be made that the ordered array is now a compressed disordered array because of material degradation of the filters and the weight of the overburden.

A set of comparison cases was modeled to determine which of the first- and second-stage filters, the $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5\text{-}7/8$ -in.) HEPA filter (see Table 2), or the $30.5 \times 30.5 \times 15$ -cm ($12 \times 12 \times 5\text{-}7/8$ -in.) filter (see Table 3) could be used as an enveloping case. The base model consisted of 200 g (7 oz) of plutonium (95% Pu-239 and 5% Pu-240) in the form of PuO_2 . The value of 200 g (7 oz) was obtained from estimates of the high loading that could be possible in the first- and second-stage smaller filters (see footnote b).

Table 2. $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5\text{-}7/8$ -in.) glovebox high-efficiency particulate air filters to determine density effects.^a

Thin Layer of Material on Filter Media			
Case Name	(g/cm ³)	k _{eff} ± 1σ	k _{eff} + 2σ
8 × 8 × 5_13a	2	0.9510 ± 0.0010	0.953
8 × 8 × 5_13b	3	0.9480 ± 0.0012	0.950
8 × 8 × 5_13c	4	0.9478 ± 0.0011	0.950
8 × 8 × 5_13d	5	0.9497 ± 0.0011	0.952
8 × 8 × 5_13e	6	0.9491 ± 0.0010	0.951
8 × 8 × 5_13f	7	0.9483 ± 0.0011	0.950
8 × 8 × 5_13g	8	0.9502 ± 0.0010	0.952
8 × 8 × 5_13h	9	0.9484 ± 0.0011	0.951
8 × 8 × 5_13i	10	0.9460 ± 0.0011	0.948
8 × 8 × 5_13j	11	0.9496 ± 0.0010	0.952
8 × 8 × 5_13k	11.46	0.9479 ± 0.0011	0.950

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g (7 oz) of plutonium per filter and saturated soil as the reflector with 100% water-flooded high-efficiency particulate air filters containing a varied density of plutonium dioxide.

The PuO₂ was assumed to be distributed evenly throughout each filter as a layer on one side of each of the sheets of filter cellulose media (see Figure 5). The density of the PuO₂ was varied from a theoretical density of 11.46 g/cm³ to a model density of 2 g/cm³. As the density decreased, the corresponding thickness of the PuO₂-containing layer and the void fraction in the PuO₂ increased. A determination case comparison was conducted to determine the more reactive configuration between a $2 \times 2 \times 1$ array and a $2 \times 1 \times 2$ array containing PuO₂ at a density of 2 g/cm³. The $2 \times 1 \times 2$ array yielded a calculated $k_{\text{eff}} + 2\sigma = 0.953$ while the $2 \times 2 \times 1$ array yielded a calculated $k_{\text{eff}} + 2\sigma = 0.894$. From the results of the scoping calculations, a $2 \times 1 \times 2$ array of filters was chosen as the base model. The filters in these comparison cases were placed at a 1-cm (0.4-in.) edge-to-edge spacing. The space between the filters was filled with water-saturated soil. The 1-cm (0.4-in.) edge-to-edge spacing was chosen in an attempt to inject a limited amount of realism into the base model. The placement of the filters into the SDA could have been in an orderly fashion but the covering of the cardboard boxes with the overburden would have led to some disruption of an array of orderly stacked cardboard boxes. However, a single case was evaluated that consisted of filters that were touching in the $2 \times 1 \times 2$ array. The results of this case are given in Table 4.

The gap between each of the filter media sheets, along with any corresponding void fraction in the PuO₂ layer on the filter media, then was flooded with water in these cases. The results of these comparison cases are found in Tables 2 and 3. An illustration of the filter used in the calculational model is provided in Figure 6. An illustration of the array of filters, as modeled in the calculation, is shown in Figure 7.

Table 3. $2 \times 1 \times 2$ array of $30.5 \times 30.5 \times 15$ -cm ($12 \times 12 \times 5$ -7/8-in.) glovebox high-efficiency particulate air filters to determine density effects.^a

Thin Layer of Material on Filter Media			
Case Name	(g/cm ³)	k _{eff} ± 1σ	k _{eff} + 2σ
12 × 12 × 6_2a	2	0.8992 ± 0.0008	0.901
12 × 12 × 6_2b	3	0.9010 ± 0.0009	0.903
12 × 12 × 6_2c	4	0.8980 ± 0.0008	0.900
12 × 12 × 6_2d	5	0.8979 ± 0.0009	0.900
12 × 12 × 6_2e	6	0.8995 ± 0.0007	0.901
12 × 12 × 6_2f	7	0.9008 ± 0.0008	0.902
12 × 12 × 6_2g	8	0.8989 ± 0.0009	0.901
12 × 12 × 6_2h	9	0.9006 ± 0.0008	0.902
12 × 12 × 6_2i	10	0.8994 ± 0.0008	0.901
12 × 12 × 6_2j	11	0.9009 ± 0.0008	0.902
12 × 12 × 6_2k	11.46	0.8997 ± 0.0009	0.902

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g (7 oz) of plutonium per filter with saturated soil as the reflector and 100% water-flooded high-efficiency particulate air filters containing a varied density of plutonium dioxide.

Table 4. Edge-to-edge spacing varied in $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5$ -7/8-in.) glovebox high-efficiency particulate air filters.^a

Case Name	Edge-to-Edge Distance Between Filters in Soil		$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
	(cm)			
$8 \times 8 \times 5_10$	0		0.9741 ± 0.0011	0.976
$8 \times 8 \times 5_10a$	1		0.9510 ± 0.0010	0.953
$8 \times 8 \times 5_10b$	2		0.9257 ± 0.0012	0.928
$8 \times 8 \times 5_10c$	3		0.9052 ± 0.0010	0.907
$8 \times 8 \times 5_10d$	4		0.8827 ± 0.0010	0.885
$8 \times 8 \times 5_10e$	5		0.8614 ± 0.0011	0.863
$8 \times 8 \times 5_10f$	10		0.7875 ± 0.0010	0.790
$8 \times 8 \times 5_10g$	20		0.7322 ± 0.0010	0.734

a. The array has 200 g (7 oz) of plutonium per filter and saturated soil as the reflector with 100% water-flooded high-efficiency particulate air filters.

These comparison cases show that the distribution of 200 g (7 oz) of plutonium in the form of PuO_2 in the smaller filter is more reactive than the same distribution in the larger filter. In addition, the

reactivity of the system is relatively insensitive to the density used for the PuO_2 layer on the filter media. Therefore, the gram density used for the PuO_2 layers in the remainder of the cases was 2 g/cm^3 .

Two more comparison cases were evaluated to determine that the initial model was enveloping for the remaining models to be developed. In the first comparison case, the $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15\text{-cm}$ ($8 \times 8 \times 5\text{-}7/8\text{-in.}$) filters with the 1-cm (0.4-in.) edge-to-edge spacing, as described earlier in this section, was evaluated with a different mandrel. In this model, the mandrel present in the filter was modeled as 0.16 cm ($1/16 \text{ in.}$). The data conflicted between superseded versions of the military specifications (Military Specifications 1970 [MIL-F-51079A] and 1980) about whether a 0.16-cm ($1/16\text{-in.}$) mandrel met the specification. To address this question, a single comparison case was evaluated. By reducing the size of the mandrel by one-third, the number of media sheets present in the filter increased three-fold while the gap spacing decreased between sheets. However, the total void in the filter was reduced only slightly because of the very thin depth of the filter media sheets. The results from the $2 \times 1 \times 2$ -array case yielded a calculated $k_{\text{eff}} + 2\sigma = 0.959$. This k_{eff} is statistically equivalent to the calculated k_{eff} for Case $8 \times 8 \times 5_10\text{a}$ (see Table 4) that was shown to be 0.953 . Therefore, the size of the mandrel, either 0.48 cm ($3/16 \text{ in.}$) or 0.16 cm ($1/16 \text{ in.}$), is not relevant to the reactivity of the model.

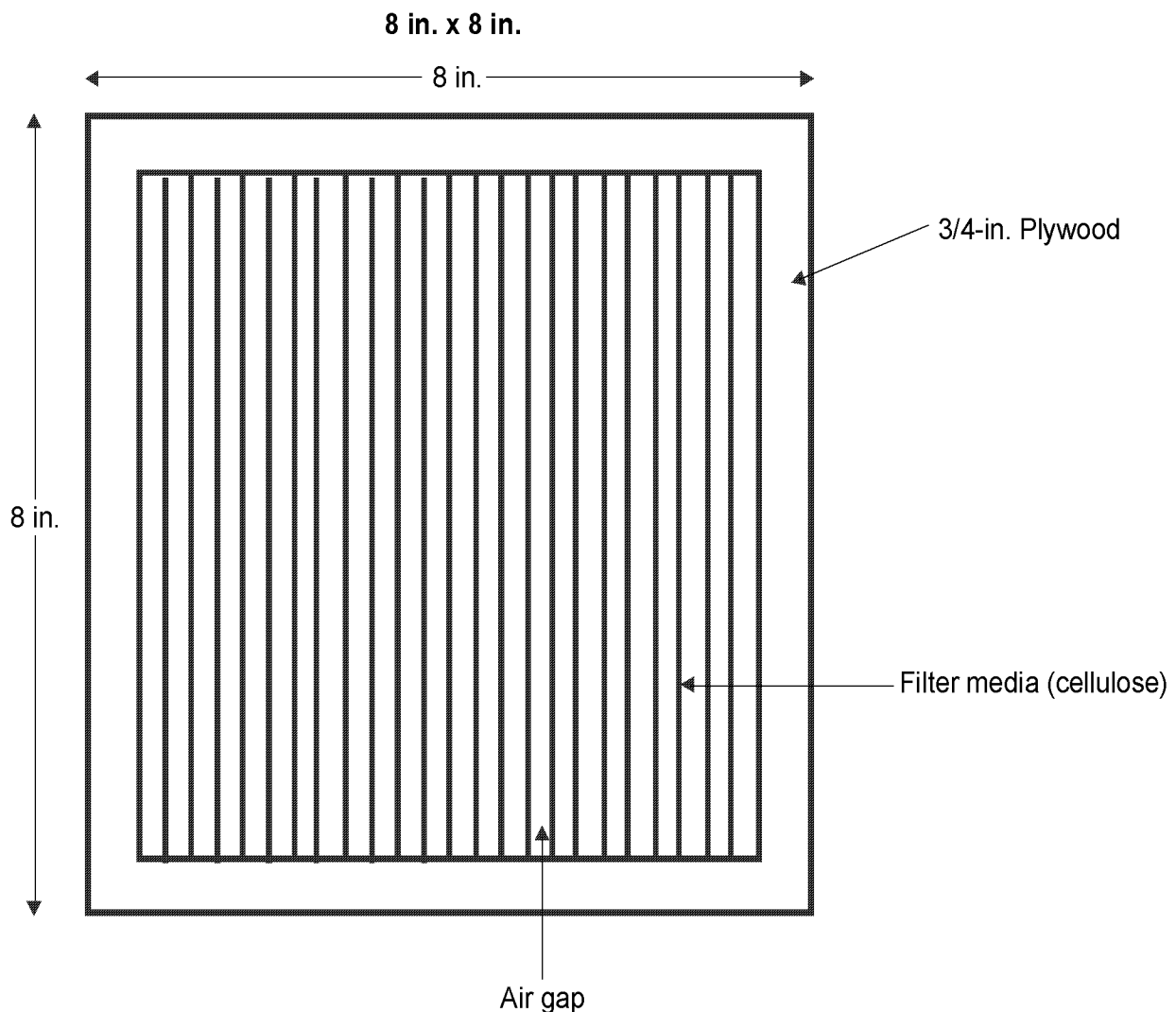


Figure 6. Planar view (x-y) of a filter as modeled for calculation purposes.

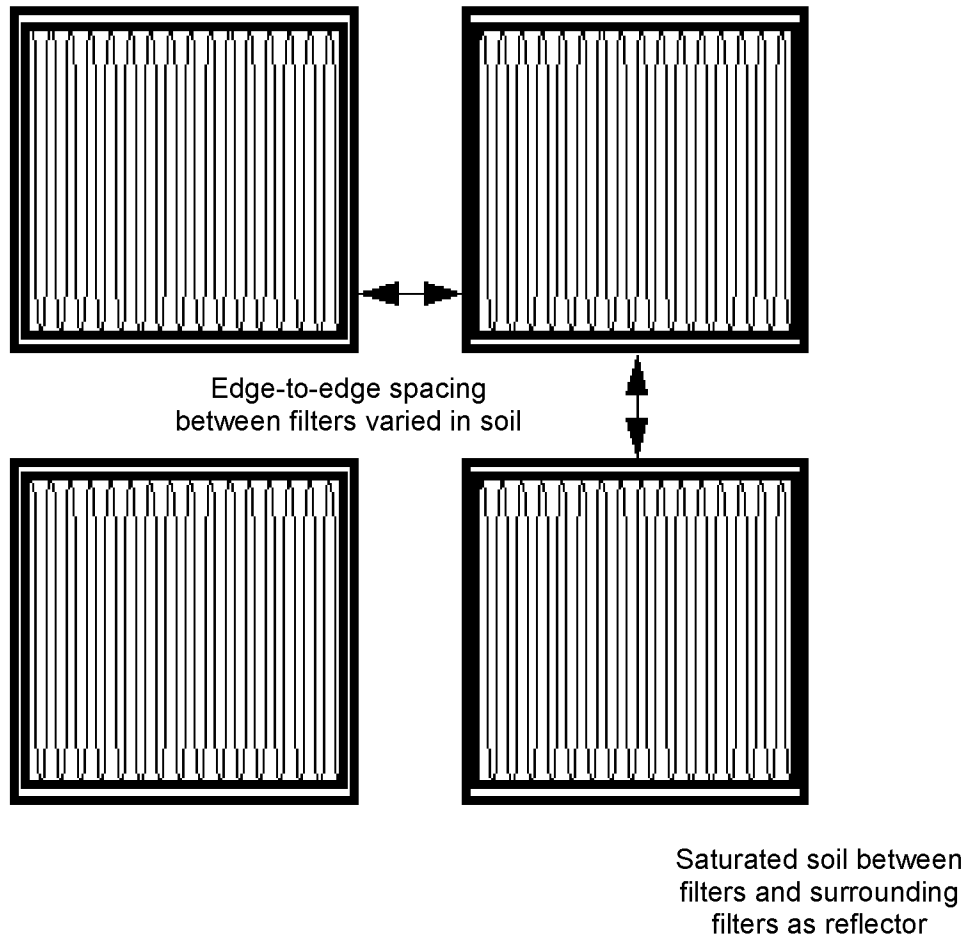


Figure 7. Planar view (x-y) of spacing of filters in soil.

In the second comparison case, the filter media sheet was evaluated at maximum thickness. The Military Specification (1980) appropriate to filter media allows for a minimum filter thickness of 0.038 cm (0.015 in.) and a maximum thickness of 0.102 cm (0.040 in.). Once again, the same configuration of filters in the $2 \times 1 \times 2$ array was considered with a maximum filter media thickness of 0.102 cm (0.040 in.). The calculated $k_{\text{eff}} + 2\sigma$ for this case was given as 0.949. This k_{eff} is statistically equivalent to the calculated k_{eff} for case $8 \times 8 \times 5_{-10a}$, which was shown to be 0.953 (see Table 4). Therefore, the thickness of the filter media sheets, 0.038 cm (0.015 in.) or 0.102 cm (0.040 in.), is not relevant to the reactivity of the model.

The base model used for the remaining cases was chosen to be the filter with the 0.48-cm (3/16-in.) mandrel and the filter media sheets with a thickness of 0.038 cm (0.015 in.). Applying this model, a parametric study was completed to determine the reactivity effect of spacing between filters in the soil.

For this set of calculations, a $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5\text{-}7/8$ -in.) filters was used. The edge-to-edge spacing between filters was varied from 0 to 20 cm (0 to 7.9 in.), as incremented in Table 4, to determine the amount of soil needed between filters to ensure a subcritical state. The results of these cases are given in Table 4. The soil between the filters was modeled as fully saturated because the 40% void fraction in the soil was filled with water. This is a valid modeling assumption because if full flooding occurs in the filters themselves, then the surrounding soil also must be fully flooded. These model calculations show that if the filters are separated by 2 cm (0.8 in.) of soil, the calculated k_{eff} will be less than 0.95. The $2 \times 1 \times 2$ array model is a very orderly array of four highly loaded filters in close proximity.

Two more arrays of filters were modeled to determine the system reactivity. A $2 \times 1 \times 3$ array of filters with a 1.0-cm (0.4-in.) separation distance between filters, as previously described, was modeled and yielded a calculated $k_{\text{eff}} + 2\sigma = 1.011$. In addition, a $2 \times 2 \times 2$ array of the same filters was modeled and yielded a calculated $k_{\text{eff}} + 2\sigma = 1.068$. A last perturbation was made to this model set. A $3 \times 3 \times 3$ array of filters containing no water in a dry-soil environment also was evaluated. Once again, the filters were separated by 1 cm (0.4 in.) of soil with a 200-g (7-oz) Pu-239 fissile loading per filter. The calculated $k_{\text{eff}} + 2\sigma$ for the $3 \times 3 \times 3$ array model was equal to 0.827. It should be emphasized that these are highly ordered arrays of highly loaded filters. This study shows that as realistic assumptions are introduced into the calculational models, the reactivity of the systems decreases dramatically.

A more-expected nominal loading per filter would be in the range of 10 to 50 g (0.4 to 1.8 oz) of plutonium per filter (Clements 1982). A set of cases was evaluated to determine how many filters would be necessary to create a critical configuration if the loading per filter was reduced from 200 g (7 oz) of plutonium per filter to 50 g (1.8 oz). The results of these cases are given in Table 5.

As shown in Table 5, when modeled filters that contain a more realistic nominal loading are placed together in an array, quite a large array of filters can be assembled and the system still remains subcritical. This effect is very important because most of the filters are expected to actually contain fissile loading in the range of 30.0-g (1.1-oz) plutonium per filter.^d

Table 5. Lower fissile-loaded filters ($20.3 \times 20.3 \times 15$ cm [$8 \times 8 \times 5\text{-}7/8$ in.]) modeled in variously sized arrays.^a

Case Name	Size of Array	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
$8 \times 8 \times 5$ _14a	$2 \times 2 \times 2$	0.6635 ± 0.0008	0.665
$8 \times 8 \times 5$ _14b	$3 \times 3 \times 3$	0.7773 ± 0.0007	0.779
$8 \times 8 \times 5$ _14c	$4 \times 4 \times 4$	0.8352 ± 0.0006	0.836
$8 \times 8 \times 5$ _14d	$5 \times 5 \times 5$	0.8704 ± 0.0006	0.872
$8 \times 8 \times 5$ _14e	$6 \times 6 \times 6$	0.8907 ± 0.0006	0.892

a. These arrays have 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 50 g (1.8 oz) of plutonium per filter with saturated soil as reflector and 100% water-flooded high-efficiency particulate are filters.

d. Almodovar, Sixto T., Enercon Innovative Solutions, Memorandum to Paul J. Sentieri, Idaho National Engineering and Environmental Laboratory, July 20, 2001, "Completion of task 3.1 of contract K00-564419-003, revision date of 05/08/01, Historical data on Rocky Flats Flanders Filter."

In the next set of cases, the effects of soil and water were evaluated as moderating materials in the gaps of the filters. It is expected (because of subsidence in the pit and degradation of the filters) that any water-moderating material introduced to the filters would be muddy in nature (a combination of soil and water). Degradation of the filters and pit subsidence during the burial period would intermix soil in the filter itself or result in crushed filter media that cannot be optimally moderated. Water intrusion then would lead to a combination of soil and water being intermixed in the filter media. The previous cases were evaluated with full-density water filling the gaps between the PuO₂-laden filter media sheets. For this series of cases, a 2 × 2 × 3 array of 20.3 × 20.3 × 15-cm (8 × 8 × 5-7/8-in.) filters (containing 200 g [7 oz] of plutonium per filter) was modeled with a combination of water and soil filling the void in the filter gaps.

The filters were modeled with an edge-to-edge spacing of 1 cm (0.4 in.). The first series of cases in this set consisted of the filter gap spacing being filled with SDA soil. The SDA soil has a void fraction of 40%. Cases were evaluated that consisted of varied amounts of water filling this 40% void fraction. The amount of water present in the void fraction varied from 0 to 100%. The results from these cases are given in Table 6.

One single case was evaluated that consisted of a 2 × 2 × 3 array of filters (Case 8 × 8 × 5_15f) that was similar to Case 8 × 8 × 5_15e. In Case 8 × 8 × 5_15f, the soil, acting as the reflector around the system and the soil interspersed between the filters, was modeled containing no water. The calculated $k_{\text{eff}} + 2\sigma$ for Case 8 × 8 × 5_15f was shown to be equal to 0.690. Again, this indicates the dependence of flooding in the system to achieve higher k_{eff} . In addition, it should be noted that this set of cases was used to evaluate a 2 × 2 × 3 array of filters. The increased array size emphasizes the dependence of reactivity on the water content or degree of saturation of the moderating material intermixed with the fissile material. As soil is introduced into the filters, the reactivity of the system decreases dramatically or more filters are needed to assemble a more reactive configuration.

Table 6. Varied fraction of water volume in soil modeled interstitially in 2 × 2 × 3 array of 20.3 × 20.3 × 15-cm (8 × 8 × 5-7/8-in.) glovebox high-efficiency particulate air filters.^a

Case Name	Fraction of Water in 40% Void Fraction in Soil in Filter (%)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
8 × 8 × 5_15a	100	0.9779 ± 0.0010	0.980
8 × 8 × 5_15b	75	0.9342 ± 0.0011	0.936
8 × 8 × 5_15c	50	0.8821 ± 0.0011	0.884
8 × 8 × 5_15d	25	0.7906 ± 0.0010	0.793
8 × 8 × 5_15e	0	0.7612 ± 0.0012	0.764

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g (7 oz) of plutonium per filter with saturated soil as the reflector SDA soil (40% water volume fraction) and water-flooded high-efficiency particulate air filters.

As shown by these results, the reactivity of the system is very dependent on the amount of water present in the filters. The next series of cases is similar to the previous set. In this set, however, the gap space between the filter media sheets is filled with a combination of soil and water at various ratios. The results of this series of cases are given in Table 7. It also should be noted that the array size is larger than

previously modeled in this case. This is because of the significant effect soil has on the reactivity of the system.

Table 7. Varied mixture of water and soil modeled interstitially in $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5$ -7/8-in.) glovebox high-efficiency particulate air filters.^a

Case Name	Volume Fraction of Water in Filter Gap Region (%)	Volume Fraction of Soil in Filter Gap Region (%)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
$8 \times 8 \times 5$ _13a	100	0	0.9510 ± 0.0010	0.953
$8 \times 8 \times 5$ _16a	90	10	0.9249 ± 0.0010	0.927
$8 \times 8 \times 5$ _16b	80	20	0.8948 ± 0.0011	0.897
$8 \times 8 \times 5$ _16c	70	30	0.8639 ± 0.0010	0.866
$8 \times 8 \times 5$ _16d	60	40	0.8291 ± 0.0011	0.831
$8 \times 8 \times 5$ _16e	50	50	0.7909 ± 0.0012	0.793

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g (7 oz) of plutonium per filter flooded with a mixture of water and soil with saturated soil as the reflector.

These results show that as soil displaces water in the filters, the calculated k_{eff} for the system decreases, which in turn indicates the effect of water moderation on the system.

The soil composition in the SDA is known to contain a certain amount of boron in the form of B_2O_3 . The nominal amount of B_2O_3 is approximately 0.05 wt% of the soil composition (Callow et al. 1991). In natural boron, the isotopic composition is approximately 20% B-10 and 80% B-11. The boron isotope B-10 has a high thermal-neutron-absorption cross-section. A set of cases was evaluated to determine the effects boron would have if included in the system. This set evaluated the $2 \times 1 \times 2$ water-moderated array of filters with an edge-to-edge spacing of 1.0 cm (0.4 in.) in water-saturated soil. The filters were loaded at 200 g (7 oz) of plutonium in the form of PuO_2 , as previously described. Boron was included in the water in the gaps between the plutonium-laden filter media. In all of the previous cases, the boron was modeled as completely comprising B-11. In this case, boron was modeled as comprising B-10 and B-11. The amount of B-10 was varied from 100% of the 19% isotopically present to 25% of the 19% isotopically present. The results of these cases are given in Table 8.

As shown in Table 8, the case in which a $2 \times 1 \times 2$ array was modeled with no B-10 yielded a $k_{\text{eff}} + 2\sigma$ of 0.953 (Case $8 \times 8 \times 5$ _10a). A comparison to this calculated k_{eff} shows the Δk difference when various amounts of B-10 from the soil are included. These results show the effects of neutronic poisons on the reactivity of the system.

Pit subsidence has occurred on a regular basis at the SDA; therefore, a set of cases was evaluated to consider these subsidence events. These cases determined the effect on reactivity if the gap spacing in the filter was reduced so that the cross-sectional area of the filter is decreased with the height and length of the filters being preserved. This decrease effectively excludes water from in the filter as the filter is compressed in the horizontal direction. This exclusion of water decreases the amount of moderator present, thus decreasing the ratio of hydrogen to plutonium. The gap spacing in the $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5$ -7/8-in.) filter was decreased uniformly over the cross section of the filter. Each gap was

reduced to approximately 75, 50, and 25% of its original width. The results from these cases are given in Table 9.

Table 8. Varied mixture of water and boron modeled interstitially in $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5$ -7/8-in.) glovebox high-efficiency particulate air filters.^a

Case Name	Weight Fraction of B-10 from Soil in Water in Filter	Total B-10 Present in the Soil (%)	Solids Parts per Million (mg/kg)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
$8 \times 8 \times 5$ _10a	0	0	0	0.9505 ± 0.0010	0.953
$8 \times 8 \times 5$ _17a	3.5×10^{-5}	100	44	0.9064 ± 0.0011	0.909
$8 \times 8 \times 5$ _17b	2.625×10^{-5}	75	32.8	0.9172 ± 0.0010	0.919
$8 \times 8 \times 5$ _17c	1.75×10^{-5}	50	21.9	0.9287 ± 0.0010	0.931
$8 \times 8 \times 5$ _17d	8.75×10^{-6}	25	10.9	0.9381 ± 0.0010	0.940

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g (7 oz) of plutonium per filter flooded with water containing B-10 with saturated soil as the reflector.

The results given in Table 9 show that as the filter is compressed, the reactivity is essentially equivalent or less than the normal filter case. Therefore, any compression of the filter will decrease the reactivity of the system or, in the case of up to approximately 75% compaction, it remains the same (in statistical uncertainty). These results show the effects of geometry and water moderation on the reactivity of the system.

Table 9. Compressed filters ($20.3 \times 20.3 \times 15$ -cm [$8 \times 8 \times 5$ -7/8-in.]) flooded with water in a $2 \times 1 \times 2$ array.^a

Case Name	Gap Thickness of Original (%)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
$8 \times 8 \times 5$ _10a	100	0.9510 ± 0.0010	0.953
$8 \times 8 \times 5$ _18a	74.5	0.9504 ± 0.0009	0.952
$8 \times 8 \times 5$ _18b	48.6	0.9196 ± 0.0011	0.922
$8 \times 8 \times 5$ _18c	22.75	0.8432 ± 0.0011	0.845

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g (7 oz) of plutonium per filter with saturated soil as the reflector and 100% water-flooded filters compressed to reduce the gap spacing in filters.

In all of the previous filter cases, PuO_2 was dispersed evenly throughout the filter as a thin layer on each of the filter media sheets. A set of cases was used to evaluate the reactivity effects of consolidating the oxide over a smaller area of each media sheet. This effect increases the thickness of the oxide layer per sheet if the total mass of PuO_2 in the filter is preserved. A schematic example of the calculational model used is given in Figure 8.

In the form of PuO_2 , 200 g (7 oz) of plutonium were spread over an area of 75, 50, 25, and 10% of the total filter surface area. A $2 \times 1 \times 2$ array of filters was modeled in saturated soil media. The filters were modeled with a 1-cm (0.4-in.) edge-to-edge spacing in the soil. As the area decreases over which the oxide is spread, the thickness of the oxide layer per sheet increases, as mentioned above. The layers of oxide were modeled so that interaction between the filters was maximized. In a single layer of the $2 \times 1 \times 2$ array, the oxide layers were modeled over the entire filter media sheets in the “x” direction and shifted in the “y” direction. The oxide was spread over the entire axial region of each filter. A schematic example of the configuration modeled is shown in Figure 9. The results from these cases are given in Table 10.

Table 10. Reduction in areal dispersion of plutonium dioxide on filter media in a $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5\text{-}7/8$ -in.) glovebox high-efficiency particulate air filters.^a

Filter Media Sheet Area of Modeled Oxide Layer			
Case Name	(%)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
$8 \times 8 \times 5$ _10a	100	0.9510 ± 0.0010	0.953
$8 \times 8 \times 5$ _20a	75	0.9086 ± 0.0010	0.911
$8 \times 8 \times 5$ _20b	50	0.8285 ± 0.0011	0.831
$8 \times 8 \times 5$ _20c	25	0.6897 ± 0.0011	0.692
$8 \times 8 \times 5$ _20d	10	0.5623 ± 0.0011	0.564

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g (7 oz) of plutonium per filter with saturated soil as the reflector and 100% water-flooded high-efficiency particulate air filters so that oxide is dispersed and reduced in the filters.

As the area decreases over which the 200 g (7 oz) of plutonium is dispersed, the calculated k_{eff} decreases, as shown in Table 10. Even though the fissile loading is preserved, the cross-sectional area of interaction between the layers of PuO_2 on adjacent filter media sheets decreases. This is a good indication of the dependence of the homogeneity on the reactivity of the system. As the plutonium in the system becomes less homogeneously distributed in the filters, the reactivity greatly decreases. This relates to the geometrical distribution of fissile material and the neutron leakage properties of the various configurations.

The next postulated configuration that was evaluated relative to the glovebox HEPA filters consisted of a single filter that was water flooded with fully saturated soil reflection. For this set of cases, the $30.5 \times 30.5 \times 15.2$ -cm ($12 \times 12 \times 6$ -in.) filters were modeled. The larger volume of this filter as compared with the $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5\text{-}7/8$ -in.) filter will allow the fissile material to be spread out over a larger volume with the presence of more moderating material. As more fissile material is distributed throughout the filter, more moderating material is excluded, thus exhibiting a tradeoff between mass of fissile material and moderator present. The results from this set of cases are given in Table 11.

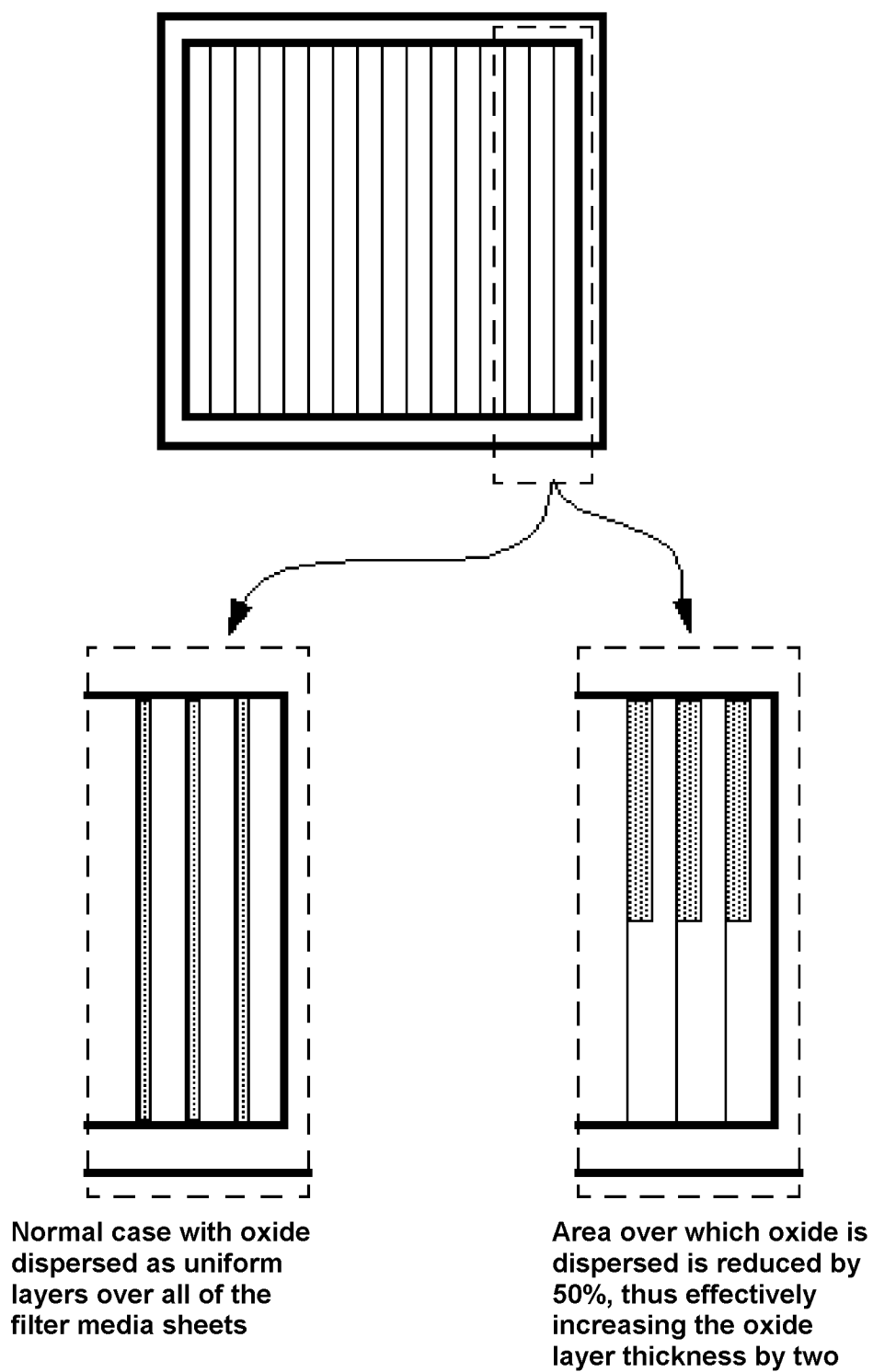


Figure 8. Example of plutonium dioxide dispersed over reduced area of filter media sheets.

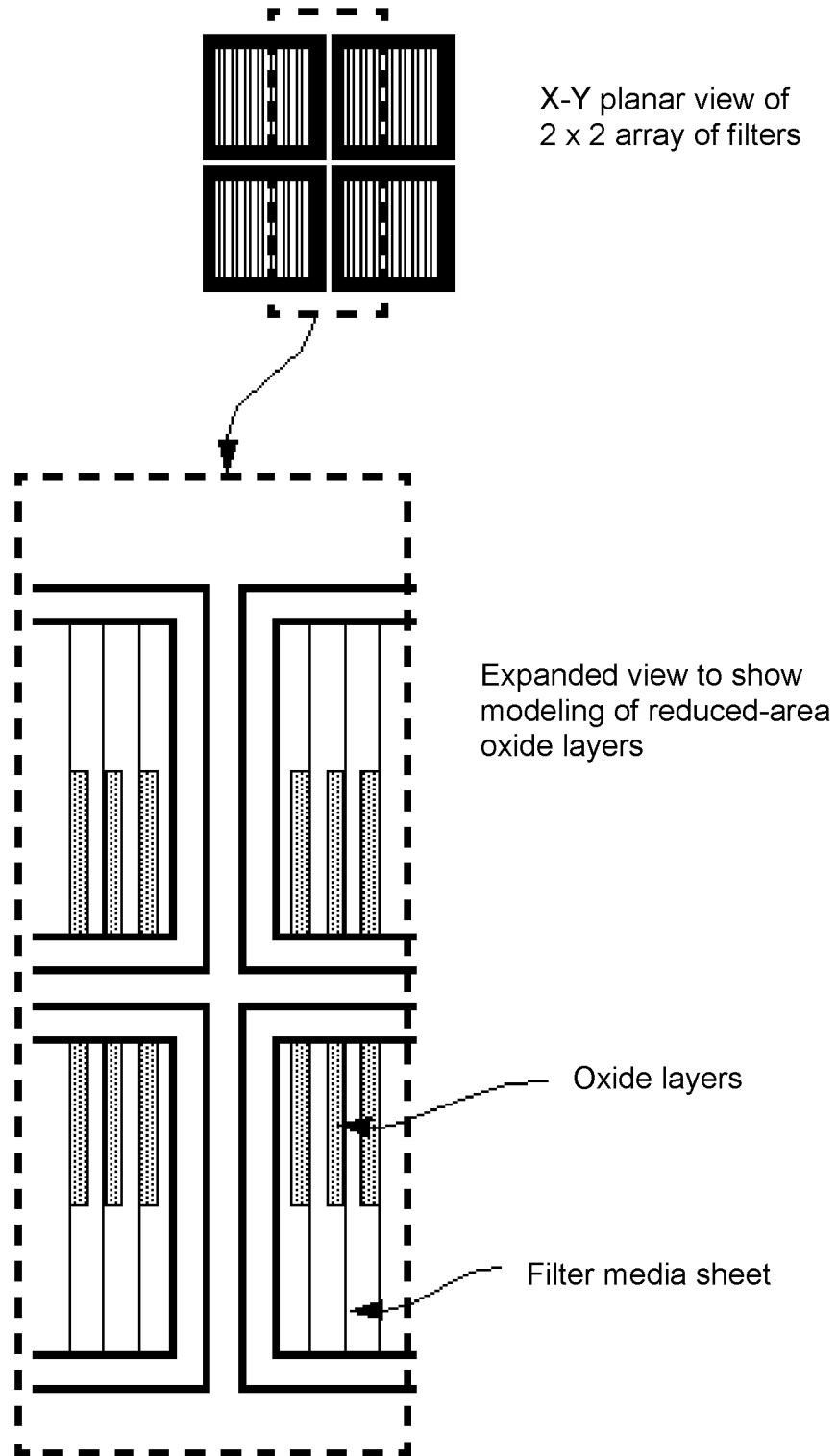


Figure 9. Example of plutonium dioxide distributed over a reduced area in filters.

The results in Table 11 show that a single filter could be overloaded with up to 800 g (28 oz) of Pu-239 and still not pose a criticality concern even for fully flooded and reflected conditions. No known historical data support filters ever having a fissile loading near the 800-g (28-oz) level. However, this model demonstrates the conservatism in the models used in this evaluation and how the distribution of fissile material, as modeled, within the filter approaches an optimum configuration. These cases show the effects of mass on the reactivity of the system.

Table 11. Single overloaded 30.5 × 30.5 × 15.2-cm (12 × 12 × 6-in.) filter in soil with 100% water in filter gaps and fully saturated Subsurface Disposal Area soil as the reflector.

Case Name	Mass of Plutonium in the Form of Plutonium Dioxide in the Filter		
	(g)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
12 × 12 × 6_3a	300	0.8016 ± 0.0011	0.804
12 × 12 × 6_3b	400	0.8648 ± 0.0011	0.867
12 × 12 × 6_3c	500	0.9090 ± 0.0010	0.911
12 × 12 × 6_3d	600	0.9390 ± 0.0012	0.941
12 × 12 × 6_3e	700	0.9610 ± 0.0012	0.963
12 × 12 × 6_3f	800	0.9757 ± 0.0012	0.978
12 × 12 × 6_3g	900	0.9887 ± 0.0012	0.991
12 × 12 × 6_3h	1,000	1.0006 ± 0.0013	1.003
12 × 12 × 6_3i	1,100	1.0060 ± 0.0012	1.008
12 × 12 × 6_3j	1,200	1.0118 ± 0.0012	1.014

In the previously evaluated cases, closely packed ordered arrays of filters were modeled. To achieve such configurations, burying the filters in cardboard boxes in an orderly stack would have been required. Then these boxes would have required enough integrity to preserve the materials comprising the filters, which is known not to be the case. The structural integrity of the filters themselves would have to have been maintained after the cardboard boxes disintegrated, which past retrieval operations have proved did not occur. The filters would need to have been loaded at the maximum fissile loading and in close proximity, which is not very probable.

The calculations performed for filters have shown that criticality can occur for or under optimal conditions and idealized systems that are not credible in the SDA. When filter spacing, diluent (soil addition), anticipated fissile mass, neutron poison (B-10), compression (as a result of degradation or subsidence), and heterogeneity are taken into account, arrays of filters are far subcritical.

6.1.2 Filters in Drums

Another set of cases was evaluated that consisted of filters housed in 55-gal drums. The scenario considered includes an array of 55-gal drums housing filters in a close-pack arrangement. In these cases, the drum was included in the model. The purpose of this set of cases was to address the issue of intact filters housed in intact drums. It is expected that if the filters were housed in either cardboard boxes or wooden boxes when disposed of, the containers would have deteriorated along with the filters. Past retrieval efforts and probing activities indicate that the drums have deteriorated. Though no intact drums are expected to be found, these cases show the effects of spacing that would be provided by intact drums.

The fissile loading per drum was modeled as 200 g (7 oz) of plutonium per drum in the form of PuO_2 dispersed on a single filter in a single drum. Three configurations of drum arrays were modeled. The three examples of configurations modeled are shown in Figure 10. In each of the three configurations, the filters were offset with each drum in an attempt to increase the interaction between the filters. Offsetting means that the filters in the drums in the upper layer were shifted down to the bottom of the drum and the filters in the drums in the bottom layer were shifted to the top of the drums. The filters were modeled as fully moderated with full-density water in the gaps between the filter media sheets. In all of the cases, the array was surrounded by fully saturated soil as a reflector and dispersed between the drums in the array. The remainder of the space in each drum outside of the filter was filled with saturated soil.

For Configuration A, the drums were modeled in a square-pitch $2 \times 2 \times 2$ arrangement with a single filter placed in each drum in an offset manner, as shown in Figure 10. In this configuration, each of the filters was rotated 45 degrees in each drum in an attempt to evaluate interaction between the filters.

For Configuration B, the drums also were modeled in a square-pitch arrangement. In this case, the filters were offset to the sides of each drum to evaluate the reactivity of this configuration.

For Configuration C, a triangular-pitch array of four drums was evaluated with the filters offset, as depicted in Figure 10. This array was evaluated to determine the reactivity difference between this arrangement and the square-pitch variations. The results from these cases are given in Table 12.

As shown by these results, when the filters are modeled as configured in a drum, the reactivity is less than 0.95. These cases demonstrate the effects of spacing (or geometry) on the reactivity of the system.

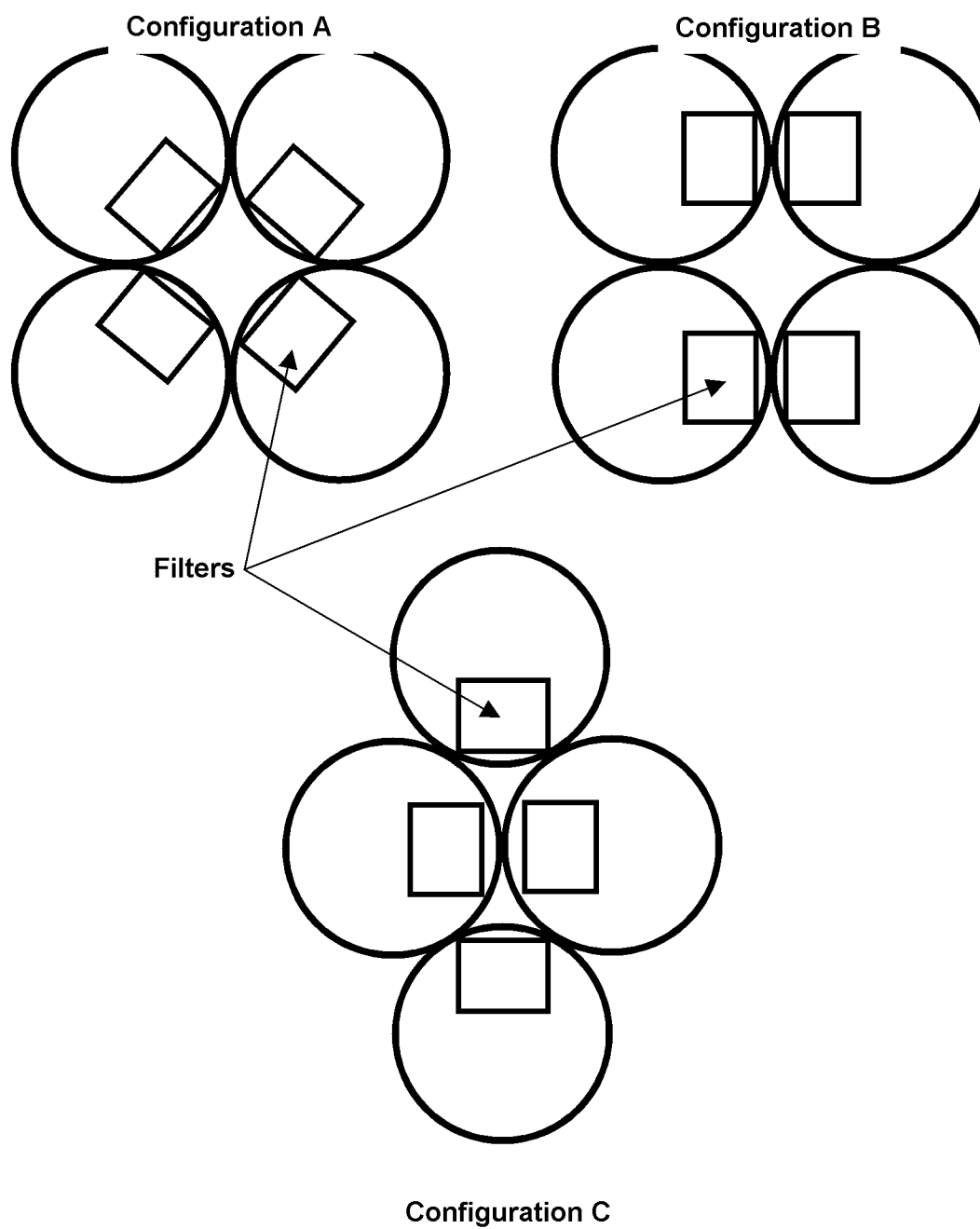


Figure 10. The x-y planar view of the drum arrays with a single filter per drum.

Table 12. A $2 \times 2 \times 2$ array of drums containing $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5\text{-}7/8$ -in.) filters showing the reactivity effects from spacing when filters are housed in drums.^a

Case Name	Configuration Modeled (from Figure 10)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
drums_1a	A	0.9413 ± 0.0010	0.943
drums_1b	B	0.9344 ± 0.0011	0.937
drums_1c	C	0.9051 ± 0.0010	0.907

a. The array has 200 g (7 oz) of plutonium per filter in the drums. The filter gap regions contain full density water. The void in the drums outside the filters is filled with saturated soil as is the area outside the drums.

6.1.3 Filters in Large Wooden Boxes

Radioactive waste was shipped to the SDA from RFP in various types of containers. The previous sections evaluated filters that possibly were shipped in either cardboard boxes or drums and were placed in the SDA. Another type of radioactive waste package used by RFP was the $1.2 \times 2.1 \times 1.2$ -m ($4 \times 7 \times 4$ -ft) large wooden waste boxes. The fissile-loading limit per large waste box was 350 g (12 oz) of fissile material. In addition, a loading restriction limited the boxes from exceeding 5 g (0.18 oz) of fissile material per cubic foot. (However, it is believed that the requirement was not implemented until the 1989 timeframe.)^e

The filter arrays that were modeled in the soil are enveloping for the possible configuration of first- and second-stage filters in the large wooden boxes. If no cubic foot in the box contained more than 5 g (0.18 oz) of plutonium and the box fissile-loading limit of 350 g (12 oz) was complied with, the distribution of the fissile material in the boxes would not be of concern.

A good argument could be made that any filter housed in a cardboard box under soil for that number of years would have decomposed and thus does not present a problem. This same argument could be made for the large wooden boxes (Thompson 1972). In addition, subsidence events at the SDA lend to the credibility of the argument that these larger boxes have experienced decomposition. Therefore, specific models were not developed for the large wooden boxes in this evaluation.

6.2 Graphite

Historical records (see footnote b) indicate that overloaded drums containing graphite as the waste matrix were discovered at RFP before shipment to the INEEL. Graphite is a waste byproduct of the process that was in use at RFP. Based on an estimate (see footnote b) of fissile material and graphite loaded at RFP for shipment to INEEL, the average loading from a sample of drums at RFP was determined to be 190 g (7 oz) of plutonium with the highest loading at 789 g (28 oz) of plutonium. In this data set, one point is identified as abnormal. A loading of 1,000 g (35 oz) of plutonium per waste drum was evaluated for this study. The estimate of 1,000 g (35 oz) of plutonium is bounding as compared to the estimated data but is consistent with the loading of some of the other overloaded drums currently in storage. These other overloaded drums are of different waste matrix forms including salts and MgO.

e. Vejvoda, Ed, Los Alamos Technical Associates, Letter to Bruce H. Becker, Idaho National Engineering and Environmental Laboratory, September 26, 2001, "Nuclear Safety – Waste Management," EV-L01039.

Various configurations were evaluated to determine the calculated k_{eff} . These model configurations and the associated results are described below.

In the first set of cases, which envelop a single overloaded drum, the reactivity was evaluated for a single drum containing 1,000 g (35 oz) of plutonium dispersed in graphite as PuO_2 at various densities. No water was modeled as interspersed in the waste matrix for this initial set of cases. The theoretical density of graphite used in the model was 2.25 g/cm^3 . This is a very conservative density and gives bounding results for this configuration because the actual density of the graphite material will be much less. The material was modeled in a spherical form reflected by saturated soil. The spherical volume was limited by the equivalent volume of a single 55-gal drum. The results of this set of cases are given in Table 13.

Table 13. Sphere of graphite and plutonium dioxide with 1,000 g (35 oz) of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Radius of Plutonium Dioxide and Graphite Sphere (cm)	Density of Plutonium Dioxide (g/cm^3)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
graphite_1a	5	2.17	0.3788 ± 0.0008	0.380
graphite_1b	10	0.271	0.4589 ± 0.0009	0.461
graphite_1c	15	0.080	0.5555 ± 0.0010	0.558
graphite_1d	20	0.034	0.6326 ± 0.0012	0.635
graphite_1e	25	0.017	0.6906 ± 0.0011	0.693
graphite_1f	30	0.010	0.7307 ± 0.0012	0.733
graphite_1g	35	0.006	0.7447 ± 0.0012	0.747
graphite_1h	37.35	0.005	0.7483 ± 0.0011	0.750

As shown by the results given in Table 13, a single drum overloaded with up to 1,000 g (35 oz) of plutonium in the form of PuO_2 and graphite will remain subcritical. These cases demonstrate the effects of mass and moderation on the reactivity of the system. In the next set of cases, the effects of combining water into the graphite and plutonium system were evaluated.

In this set of cases, 1,000 g (35 oz) of plutonium in the form of PuO_2 and graphite were combined with water in various amounts. Once again, a spherical geometry was used. The amount of graphite present corresponds to the maximum amount that could be stored in a 55-gal drum. The density of the graphite in spherical form was reduced by 10, 20, 30, and 40%, with the void fraction being filled with water. The PuO_2 was dispersed over the entire volume of the sphere. The results of these cases are given in Table 14.

As shown by these results, even though water is introduced into the system, the 1,000 g (35 oz) of plutonium in the form of PuO_2 does not form a critical system. However, it does show that peak reactivity occurs with a 10% volume fraction that is filled with water. The volume fractions in the drum containing graphite molds will be more on the order of 40 to 50%. The 20% void fraction, which was near the peak reactivity and closer to what is expected in the actual packing fraction, was chosen for the remainder of the cases. These cases also demonstrate the effects of moderation and mass on the reactivity of the system.

Table 14. Sphere of graphite, water, and plutonium dioxide with 1,000 g (35 oz) of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Volume Fraction Occupied by Water (%)	Hydrogen to Plutonium Ratio	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
graphite_2a	10	596	0.9520 ± 0.0010	0.954
graphite_2b	20	1,342	0.9422 ± 0.0008	0.944
graphite_2c	30	2,300	0.8678 ± 0.0007	0.869
graphite_2d	40	3,578	0.7600 ± 0.0005	0.761

A single intact drum loaded with various fissile material amounts was evaluated. This drum was reflected by fully saturated soil. In each of these cases, the drum was modeled completely full of graphite at 80% of its full density with a 20% void fraction that was modeled filled with water. In each case, the PuO_2 was modeled as dispersed over the entire drum. The results of this evaluation are given in Table 15.

Table 15. Drum of graphite, water, and plutonium dioxide with varied gram amounts of plutonium in the form of plutonium dioxide in a single overloaded drum.

Case Name	Quantity of Plutonium in the Drum (g)	Hydrogen to Plutonium Ratio	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
graphite_4a1a	200	6,085	0.3391 ± 0.0004	0.400
graphite_4a1b	400	3,042	0.5501 ± 0.0006	0.551
graphite_4a1c	600	2,028	0.6921 ± 0.0007	0.693
graphite_4a1d	800	1,521	0.7978 ± 0.0008	0.799
graphite_4a1e	1,000	1,217	0.8738 ± 0.0010	0.876
graphite_4a1f	1,200	1,014	0.9320 ± 0.0010	0.934

As shown by the results of the single drum cases, the 1,000 g (35 oz) of plutonium in a single drum of 80% density graphite with the 20% void fraction being filled with water does not yield a critical system. Once again, this is a very conservative model with the PuO_2 modeled as dispersed homogeneously throughout the drum in the graphite matrix. In reality, the plutonium likely would be dispersed in a more heterogeneous manner in cracks and fissures in the graphite molds.

A case was evaluated in which the model consisted of PuO_2 dispersed in a layer over a spherical chunk of graphite. A square-pitched array of these spheres was then modeled filling up the volume in a drum. The void space in the drum was filled with water. The mass of the PuO_2 associated with the 1,000 g (35 oz) of plutonium spread evenly over the total surface is represented by the spheres in this array. In other words, the thickness of the PuO_2 layer coating each spherical chunk of graphite was determined by evenly dividing the entire volume of the PuO_2 (represented by 1,000 g [35 oz] of plutonium) over the total spheres present. In this case, the spherical graphite chunks were modeled as having a 2.5-cm (1-in.) radius. The array contained 1,547 spheres with a layer of PuO_2 7.18×10^{-4} cm (2.8×10^{-4} in.) thick on each sphere. The spheres were modeled as nearly touching in the drum. The $k_{\text{eff}} + 2\sigma$ for this case was

calculated to be 0.719. These cases demonstrate the geometrical effects of the distribution of homogeneous or heterogeneous fissile material in the system.

A last set of cases was evaluated to determine the calculated k_{eff} for various drum arrays containing 1,000 g (35 oz) of plutonium in the form of oxide in a single drum of graphite waste material. The remaining drums in the array contained 200 g (7 oz) of plutonium in the form of oxide in graphite waste material. The graphite was modeled as 80% of theoretical density with the 20% void fraction being filled with water. Various sized drum arrays were modeled as fully reflected by water-saturated soil. The results of these cases are given in Table 16.

Table 16. Arrays of drums in soil with 1,000 g (35 oz) of plutonium in a single drum of graphite waste material in the form of plutonium dioxide, water, and 20%-density graphite.^a

Case Name	Size of Array Modeled	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
graphite_4a3	$3 \times 3 \times 2$	0.9008 ± 0.0008	0.902
graphite_4b3	$3 \times 2 \times 2$	0.8941 ± 0.0009	0.896
graphite_4c3	$2 \times 2 \times 2$	0.8906 ± 0.0009	0.892
graphite_4d3	$2 \times 2 \times 1$	0.8838 ± 0.0008	0.885

a. The remaining drums in the array are modeled with 200 g (7 oz) of plutonium per drum.

The physical form of the graphite waste consists of broken molds or pieces of molds that inherently make optimal conditions not possible in belowground waste. The fissile material in the waste is not homogeneous, optimal moderation cannot occur without mechanical force, and the waste matrix itself is a diluent for drum-sized volumes. The addition of soil, which will occur with drum degradation, will only reduce reactivity.

6.3 Magnesium Oxide

Records show that a number of the overloaded drums currently segregated in the aboveground storage facilities at the RWMC contain MgO as the waste matrix. Magnesium oxide is a waste byproduct of a process that was in use at RFP. Assaying of the overloaded drums in the aboveground storage facilities at the RWMC shows the maximum overloaded drum containing MgO has a fissile loading of 1,360 g (48 oz). For this study, a loading of 1,500 g (53 oz) of plutonium in a single waste drum was evaluated. Various configurations were evaluated to determine the calculated k_{eff} . These model configurations and the associated results are described below.

Heels from the bottoms of crucibles were evaluated in the modeling. The actual heels were likely hemispherical in shape and likely consisted of broken pieces. The discrete pieces would preclude the fissile material from being dispersed homogeneously in this waste matrix and, therefore, would decrease the likelihood of a critical system being formed.

In the first set of cases, which envelops a single overloaded drum, the reactivity was evaluated of 1,500 g (53 oz) of plutonium dispersed in MgO as PuO_2 at various densities. The theoretical density of MgO that was used was 3.58 g/cm^3 . Again, this is a very conservative theory and will give bounding results for this configuration. The material was modeled in a spherical form reflected by saturated soil. The results of this set of cases are given in Table 17.

As shown by the results given in Table 18, a single drum overloaded with up to 1,500 g (53 oz) of plutonium in the form of PuO₂ and MgO will remain subcritical. However, to a limited degree (as a result of the moderating material being MgO), these cases show the effects of mass and lack of moderation on the reactivity of the system. In the next set of cases, the effects of combining water into the MgO and plutonium system were evaluated.

In this set of cases, 1,500 g (53 oz) of plutonium in the form of PuO₂ and MgO were combined with various amounts of water. Again, a spherical geometry was used. The density of the MgO was reduced from 10 to 50% incrementally with the void fraction being filled with water. The PuO₂ was dispersed over the entire volume of the sphere. The results of these cases are given in Table 18.

Table 17. Sphere of magnesium oxide and plutonium dioxide with 1,500 g (53 oz) of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Radius of Plutonium Dioxide and Magnesium Oxide Sphere (cm)	Density of Plutonium Dioxide (g/cm ³)	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
mgo_1a	5	3.25	0.3759 ± 0.0006	0.377
mgo_1b	10	0.41	0.2979 ± 0.0007	0.299
mgo_1c	15	0.12	0.3213 ± 0.0007	0.323
mgo_1d	20	0.05	0.3554 ± 0.0008	0.357
mgo_1e	25	0.026	0.3884 ± 0.0007	0.390
mgo_1f	30	0.015	0.4292 ± 0.0009	0.431
mgo_1g	35	0.009	0.4748 ± 0.0009	0.476
mgo_1h	37.35	0.008	0.4958 ± 0.0008	0.497

Table 18. Sphere of magnesium oxide, water, and plutonium dioxide with 1,500 g (53 oz) of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Volume Fraction Occupied by Water (%)	Ratio of Hydrogen to Plutonium	$k_{\text{eff}} \pm 1\sigma$	$k_{\text{eff}} + 2\sigma$
mgo_2a	10	450	0.8315 ± 0.0009	0.833
mgo_2b	20	1,014	0.8953 ± 0.0008	0.897
mgo_2c	30	1,738	0.8706 ± 0.0008	0.872
mgo_2d	40	2,704	0.8033 ± 0.0006	0.805
mgo_2e	50	4,057	0.7046 ± 0.0005	0.706

These cases are somewhat misleading because the plutonium was modeled as if dispersed homogeneously throughout the MgO matrix, when in reality it would be in a more heterogeneous form. Magnesium oxide is similar to SiO₂ in that it has a low absorption cross section. Therefore, a larger

system is necessary to achieve a critical system and the dispersion of the oxide causes the reactivity to be lower.

The physical form of the MgO waste comprises broken molds and or pieces of molds that inherently make optimal conditions not possible in belowground waste. The fissile material in the waste is not homogeneous; therefore, optimal moderation cannot occur without mechanical force and unless the waste matrix itself is a diluent for drum-sized quantities. The addition of soil that will occur with drum degradation will only further reduce reactivity.

7. DESIGN FEATURES AND ADMINISTRATIVE CONTROLS

The design features and administrative controls normally associated with the proposed operations are not directly applicable because this study concerns waste already buried in the SDA. The one design feature that could be implemented is the exclusion of water. If, by engineered means, water could be excluded from the SDA, then the likelihood of a critical configuration forming would be beyond extremely unlikely with a probability very near zero.

8. SUMMARY

Various configurations involving three waste matrices of concern, glovebox HEPA filters, graphite, and MgO, are discussed in this study. The calculational models for these configurations, by nature, are very conservative. In addition, the forms and distributions in the SDA are not well known. Therefore, to better capture the nature of the problem, incorporating very conservative assumptions is necessary to determine what is required to form a critical configuration and then evaluate whether or not these conditions can occur.

Various parameters were investigated to determine the effects of k_{eff} on the reactivity of the various configurations. As shown by the various models evaluated, when very conservative assumptions are used, high system reactivity can be postulated for highly ordered arrays of HEPA filters and highly overloaded graphite and MgO drums and drum arrays. When credit is taken for expected mass of fissile material, presence of moderating material, geometrical configuration, presence of diluents and neutronic poisons, reflection conditions, and concentration and distribution of the fissile material, criticality is shown to be not credible. The varied parameters and the results from these studies are summarized in Table 19.

In most of the cases, unless otherwise specified, the model consisted of a $2 \times 1 \times 2$ array of $20.3 \times 20.3 \times 15$ -cm ($8 \times 8 \times 5$ -7/8-in.) filters with 200 g (7 oz) of plutonium loading per filter. The filters in the array have a 1-cm (0.4-in.) edge-to-edge spacing in a fully saturated SDA soil system. The density of the oxide on the filter media sheets was modeled as 2 g/cm^3 .

Table 19. Summary of Δk for calculated k_{eff} for various model permutations.

Parameter Varied	Maximum $k_{\text{eff}} + 2\sigma$ in Set of Cases	Minimum $k_{\text{eff}} + 2\sigma$ in Set of Cases	Δk Between Maximum and Minimum
Spacing: Edge-to-edge spacing between filters in $2 \times 1 \times 2$ array (with spacing from 1 to 20-cm [0.4 to 7.8-in.])	0.953	0.734	0.219
Mass: 50 g (1.8 oz) per filter with 1-cm (0.4-in.) edge-to-edge spacing in $2 \times 2 \times 2$, $3 \times 3 \times 3$, $4 \times 4 \times 4$, $5 \times 5 \times 5$, and $6 \times 6 \times 6$ arrays	0.892	0.665	0.227
Diluent and moderation: Subsurface Disposal Area (SDA) soil in filters (40% water volume fraction [wvf]) with the wvf in soil in filters varying from 100 to 0% in $2 \times 2 \times 3$ array	0.980	0.764	0.216
Diluent and moderation: Filter gaps filled with soil-water combinations, 90% wvf with 10% soil to 50% wvf with 50% soil, in $2 \times 2 \times 3$ array	0.927	0.793	0.134
Neutronic poison: Weight fraction of B-10 in water in filter gaps, 0 (i.e., no B-10 from SDA soil) to 8.75×10^{-6} (i.e., 100% of B-10 from SDA soil) in $2 \times 1 \times 2$ array	0.953	0.909	0.044

Table 19. (continued).

Parameter Varied	Maximum $k_{\text{eff}} + 2\sigma$ in Set of Cases	Minimum $k_{\text{eff}} + 2\sigma$ in Set of Cases	Δk Between Maximum and Minimum
Moderation: Reduced gap spacing between filter media sheets, 100 to 25% gap in $2 \times 1 \times 2$ array	0.953	0.845	0.108
Concentration and distribution: Reduction in area over filter media sheet in which PuO_2 is distributed, 100 to 10% of area in $2 \times 1 \times 2$ array	0.953	0.564	0.389
Mass: Various overload quantities in a single filter, 1,000 g (35 oz) to 300 g (11 oz) of plutonium	1.003	0.804	0.199
Mass: Single overloaded graphite drum with 1,000 g (35 oz) of plutonium modeled as PuO_2 dispersed over entire volume of drum with water or as discrete layers of PuO_2 over spherical chunks of graphite	0.876	0.719	0.157

9. CONCLUSIONS

As shown by the study, a postulated criticality safety assessment of the SDA is dependent on numerous known factors that affect criticality. These factors include the amount of fissile mass present, amount of moderator present, the geometrical configurations, the presence of diluents or neutronic poisons, the reflection conditions surrounding the fissile systems, and the concentration or distribution of the fissile material in the waste. Most of these factors would need to be optimized in some combination to achieve a critical system. As deviations from optimum conditions occur, the reactivity of the systems decreases dramatically.

As stated earlier, the potential exists for a waste package to contain a critical mass. However, it would be extremely difficult for packages with even kilogram quantities of fissile material to achieve criticality. Also, all the scenarios require near-optimum moderation (i.e., water).

The models evaluated in this study were designed to show the effects that various factors have on the reactivity of the system.

9.1.1 Fissile Mass

As shown by the filter cases loaded with 50 g (1.8 oz) of Pu-239 each, even with the large number of filters, the systems were shown to remain subcritical. These cases included near-optimum moderation and near-homogeneous distribution of fissile material. As the masses in the filters were increased to the maximum expected fissile loading with near-optimum moderation, postulated criticality scenarios were theoretically achievable with a smaller number of filters. Again, the expected configuration in the SDA does not lend itself to such idealized configurations.

9.1.2 Moderator

When deviation from near-optimum moderation occurs, more fissile material is necessary to postulate a critical system. Water is key to postulating any sort of scenario involving criticality in the confines of the SDA. Cases were evaluated to show the effects of moderator exclusion. The scenarios evaluated (1) compressed-filters and (2) intrusion of soil and water into the air gap in the filters. Water also was included in the graphite and MgO cases to show how the addition of water increases reactivity. In the most reactive postulated models, the water was dispersed in the systems in a nearly optimum configuration. As deviations from this near-optimum configuration occurred, the reactivity of the systems decreased.

9.1.3 Geometry

The models evaluated in this study consist of ordered arrays pertaining to the geometrical configuration of the filters and the near-homogeneous distribution of fissile materials in the waste matrices. In these idealistic computational models, reactive systems can be postulated. However, in realistic burial conditions, the reactivity of the systems would be much less. As the geometry of the filter array becomes more random and the space between filters is increased, the reactivity of the system decreases. The reactivity of the system also decreases as the fissile material distribution becomes less ordered and nearly optimum.

9.1.4 Diluents and Neutronic Poisons

As shown in the models, the introduction of nonfissile diluents, which allows for exclusion of the moderator and absorption of neutrons from the system, has a large effect on the reactivity of the systems. The presence of diluents in varying degrees was evaluated in the idealized models. In addition, the possible effects of B-10 contained in the soil and becoming soluble in the moderator present in the system were evaluated and shown to have little effect on the reactivity of the system. The effect is minimal because of the small amount of B-10 originally present in the soil.

9.1.5 Reflection

Reflection was evaluated by modeling a case in which the filter and fissile material system were both near optimum moderation with the soil surrounding the system being void of water. The lack of water in the reflecting layer increased the neutron leakage away from the fissile system. When compared with a similar fissile system containing a fully saturated soil reflector, the reactivity of the system lacking water in the reflector yielded a much lower calculated effective multiplication factor (k_{eff}).

9.1.6 Concentration and Distribution of Fissile Material

The distribution and concentration of fissile material throughout each filter media sheet within each filter is very conservative. Models were evaluated to show the effects of decreasing the area over which the fissile material is distributed in each of the filters. As shown by the evaluated models, as the concentration and distribution of the fissile material deviates from near optimum conditions the reactivity of the system decreases.

9.1.7 Conclusion

The conclusion of this report is that a criticality in the SDA, as currently configured is not credible. However, as previously stated, enough fissile mass exists in the SDA that, with postulated idealized conditions, the probability is not zero. The models developed for this study show the correlation between

the factors affecting criticality and the effects of these factors on the reactivity on the system. This study provides a basis that shows the effects of incorporating realism into the calculational model to simulate actual systems at the SDA. Based on the results of this study, the SDA, as currently configured, is shown to be in a subcritical state and will remain subcritical for the postulated flooding scenarios.

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Appendix A

**Excel Spreadsheets—Calculated Inputs
for Computational Model**

Appendix A

Excel Spreadsheets—Calculated Inputs for Computational Model

The spreadsheets in this appendix contain the mathematical calculations to produce the input parameters used in the computational models.

Table A-1. Computational data for a 20.3 × 20.3 × 15.2-cm (8 × 8 × 6-in.) filter.

09/24/2001 10:30													
Z length of Filter Media (cm)	14.9225												
Y Length of Filter Media (cm)	16.51												
Area of One Sheet (cm2)	246.370475												
# of Sheets in Filter	32												
Total Area of Filter Media (cm2)	7883.8552												
MA Pu239(95%) Pu240 (5%)	239.1021												
MA Pu239	239.0521												
MA Pu240	240.0538												
MA Pu239(95%) Pu240 (5%)O2	271.1009												
Density of PuO2 (g/cm3)	11.46												
Grams of Pu (g)	200 150												
Grams of PuO2 (g)	226.77 170.07												
Gram Density of PuO2	1	2	3	4	5	6	7	8	Gram Density of PuO2	9	10	11	11.46
Mass of PuO2 (g)	226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77	Mass of PuO2 (g)	226.77	226.77	226.77	226.77
Volume of PuO2 (cm3)	226.77	113.38	75.59	56.69	45.35	37.79	32.40	28.35	Volume of PuO2 (cm3)	25.20	22.68	20.62	19.79
N ²³⁹	2.1107E-03	4.2214E-03	6.3321E-03	8.4428E-03	1.0553E-02	1.2664E-02	1.4775E-02	1.6886E-02	N ²³⁹	1.8996E-02	2.1107E-02	2.3218E-02	2.4188E-02
N ²⁴⁰	1.1063E-04	2.2125E-04	3.3188E-04	4.4250E-04	5.5313E-04	6.6375E-04	7.7438E-04	8.8500E-04	N ²⁴⁰	9.9563E-04	1.1063E-03	1.2169E-03	1.2678E-03
N ^O	4.4426E-03	8.8853E-03	1.3328E-02	1.7771E-02	2.2213E-02	2.6656E-02	3.1098E-02	3.5541E-02	N ^O	3.9984E-02	4.4426E-02	4.8869E-02	5.0913E-02
N ^H	6.0911E-02	5.5088E-02	4.9265E-02	4.3441E-02	3.7618E-02	3.1795E-02	2.5972E-02	2.0148E-02	N ^H	1.4325E-02	8.5019E-03	2.6787E-03	0.0000E+00
N ^O	3.0456E-02	2.7544E-02	2.4632E-02	2.1721E-02	1.8809E-02	1.5897E-02	1.2986E-02	1.0074E-02	N ^O	7.1626E-03	4.2510E-03	1.3393E-03	0.0000E+00
N ^{O Tot}	3.4898E-02	3.6429E-02	3.7960E-02	3.9491E-02	4.1022E-02	4.2553E-02	4.4084E-02	4.5615E-02	N ^{O Tot}	4.7146E-02	4.8677E-02	5.0208E-02	5.0913E-02
N ^{Tot}	9.8031E-02	9.5960E-02	9.3889E-02	9.1818E-02	8.9747E-02	8.7676E-02	8.5605E-02	8.3534E-02	N ^{Tot}	8.1463E-02	7.9392E-02	7.7321E-02	7.6369E-02
H/Pu Ratio	28.86	13.05	7.78	5.15	3.56	2.51	1.76	1.19		0.75	0.40	0.12	0.00
Mass of PuO2 (g)	170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07	Mass of PuO2 (g)	170.07	170.07	170.07	170.07
Volume of PuO2 (cm3)	170.07	85.04	56.69	42.52	34.01	28.35	24.30	21.26	Volume of PuO2 (cm3)	18.90	17.01	15.46	14.84
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.02876	0.01438	0.00959	0.00719	0.00575	0.00479	0.00411	0.00360	Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.00320	0.00288	0.00261	0.00251
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.01438	0.00719	0.00479	0.00360	0.00288	0.00240	0.00205	0.00180	Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.00160	0.00144	0.00131	0.00125
Thickness of PuO2 Layer Single Side of Media 150 g PuO2	0.02157	0.01079	0.00719	0.00539	0.00431	0.00360	0.00308	0.00270	Thickness of PuO2 Layer Single Side of Media 150 g PuO2	0.00240	0.00216	0.00196	0.00188
Thickness of PuO2 Layer Both Sides of Media 150 g PuO2	0.01079	0.00539	0.00360	0.00270	0.00216	0.00180	0.00154	0.00135	Thickness of PuO2 Layer Both Sides of Media 150 g PuO2	0.00120	0.00108	0.00098	0.00094
Gram Density of PuO2	1	2	3	4	5	6	7	8	Gram Density of PuO2	9	10	11	11.46
Coordinates	Coordinates												
200 g Single Layer +x from Media of +x = 0.0381	0.06686	0.05248	0.04769	0.04529	0.04385	0.04289	0.04221	0.04170	200 g Single Layer +x from Media of +x = 0.0381	0.04130	0.04098	0.04071	0.04061
150 g Single Layer +x from Media of +x = 0.0381	0.05967	0.04889	0.04529	0.04349	0.04241	0.04170	0.04118	0.04080	150 g Single Layer +x from Media of +x = 0.0381	0.04050	0.04026	0.04006	0.03998
200 g Double Layer +x from Media of +x = 0.0	0.01438	0.00719	0.00479	0.00360	0.00288	0.00240	0.00205	0.00180	200 g Double Layer +x from Media of +x = 0.0	0.00160	0.00144	0.00131	0.00125
200 g Double Layer +x of Media	0.05248	0.04529	0.04289	0.04170	0.04098	0.04050	0.04015	0.03990	200 g Double Layer +x of Media	0.03970	0.03954	0.03941	0.03935
200 g Double Layer +x from Media of +x	0.06686	0.05248	0.04769	0.04529	0.04385	0.04289	0.04221	0.04170	200 g Double Layer +x from Media of +x	0.04130	0.04098	0.04071	0.04061
200 g Double Layer +x of water channel for +x PuO2	0.52873	0.52154	0.51914	0.51795	0.51723	0.51675	0.51640	0.51615	200 g Double Layer +x of water channel for +x PuO2	0.51595	0.51579	0.51566	0.51560
150 g Double Layer +x from Media of +x = 0.0	0.01079	0.00539	0.00360	0.00270	0.00216	0.00180	0.00154	0.00135	150 g Double Layer +x from Media of +x = 0.0	0.00120	0.00108	0.00098	0.00094
150 g Double Layer +x of Media	0.04889	0.04349	0.04170	0.04080	0.04026	0.03990	0.03964	0.03945	150 g Double Layer +x of Media	0.03930	0.03918	0.03908	0.03904
150 g Double Layer +x from Media of +x	0.05967	0.04889	0.04529	0.04349	0.04241	0.04170	0.04118	0.04080	150 g Double Layer +x from Media of +x	0.04050	0.04026	0.04006	0.03998
150 g Double Layer +x of water channel for +x PuO2	0.52514	0.51974	0.51795	0.51705	0.51651	0.51615	0.51589	0.51570	150 g Double Layer +x of water channel for +x PuO2	0.51555	0.51543	0.51533	0.51529

Table A-2. Calculational data for a 30.5 × 30.5 × 15.2-cm (12 × 12 × 6-in.) filter.

09/24/2001 10:30															
Y length of Filter Media (cm)		26.67													
Z Length of Filter Media (cm)		14.9225													
Area of One Sheet (cm2)		397.983075													
# of Sheets in Filter		52													
Total Area of Filter Media (cm2)		20695.1199													
MA Pu239		239.0521													
MA Pu240		240.0538													
MA Pu239(95%) Pu240 (5%)		239.1021													
MA Pu239(95%) Pu240 (5%)O2		271.1009													
Density of PuO2 (g/cm3)		11.46													
Grams of Pu (g)		200		150											
Grams of PuO2 (g)		226.77		170.07											
Gram Density of PuO2		1	2	3	4	5	6	7	8	Gram Density of PuO2		9	10	11	11.46
Mass of PuO2 (g)		226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77	Mass of PuO2 (g)		226.77	226.77	226.77	226.77
Volume of PuO2 (cm3)		226.77	113.38	75.69	56.69	45.35	37.79	32.40	28.35	Volume of PuO2 (cm3)		25.20	22.68	20.62	19.79
N ²³⁹		2.1107E-03	4.2214E-03	6.3321E-03	8.4428E-03	1.0553E-02	1.2664E-02	1.4775E-02	1.6886E-02	N ²³⁹		1.8996E-02	2.1107E-02	2.3218E-02	2.4188E-02
N ²⁴⁰		1.1063E-04	2.2125E-04	3.3188E-04	4.4250E-04	5.5313E-04	6.6375E-04	7.7438E-04	8.8500E-04	N ²⁴⁰		9.9563E-04	1.1063E-03	1.2169E-03	1.2678E-03
N ^O		4.4426E-03	8.8853E-03	1.3328E-02	1.7771E-02	2.2213E-02	2.6656E-02	3.1098E-02	3.5541E-02	N ^O		3.9984E-02	4.4426E-02	4.8869E-02	5.0913E-02
N ^H		6.0911E-02	5.5088E-02	4.9265E-02	4.3441E-02	3.7618E-02	3.1795E-02	2.5972E-02	2.0148E-02	N ^H		1.4325E-02	8.5019E-03	2.6787E-03	0.0000E+00
N ^O		3.0456E-02	2.7544E-02	2.4632E-02	2.1721E-02	1.8809E-02	1.5897E-02	1.2986E-02	1.0074E-02	N ^O		7.1626E-03	4.2510E-03	1.3393E-03	0.0000E+00
N ^{O Tot}		3.4898E-02	3.6429E-02	3.7960E-02	3.9491E-02	4.1022E-02	4.2553E-02	4.4084E-02	4.5615E-02	N ^{O Tot}		4.7146E-02	4.8677E-02	5.0208E-02	5.0913E-02
N ^{Tot}		9.80306E-02	9.59596E-02	9.38887E-02	9.18178E-02	8.97469E-02	8.76760E-02	8.56051E-02	8.35342E-02	N ^{Tot}		8.14632E-02	7.93923E-02	7.73214E-02	7.63688E-02
H/Pu Ratio		28.86	13.05	7.78	5.15	3.56	2.51	1.76	1.19			0.75	0.40	0.12	0.00
Mass of PuO2 (g)		170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07	Mass of PuO2 (g)		170.07	170.07	170.07	170.07
Volume of PuO2 (cm3)		170.07	85.04	56.69	42.52	34.01	28.35	24.30	21.26	Volume of PuO2 (cm3)		18.90	17.01	15.46	14.84
Thickness of PuO2 Layer Single Side of Media 200g PuO2		0.01096	0.00548	0.00365	0.00274	0.00219	0.00183	0.00157	0.00137	Thickness of PuO2 Layer Single Side of Media 200g PuO2		0.00122	0.00110	0.00100	0.00096
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2		0.00548	0.00274	0.00183	0.00137	0.00110	0.00091	0.00078	0.00068	Thickness of PuO2 Layer Both Sides of Media 200 g PuO2		0.00061	0.00055	0.00050	0.00048
Thickness of PuO2 Layer Single Side of Media 150 g PuO2		0.00822	0.00411	0.00274	0.00205	0.00164	0.00137	0.00117	0.00103	Thickness of PuO2 Layer Single Side of Media 150 g PuO2		0.00091	0.00082	0.00075	0.00072
Thickness of PuO2 Layer Both Sides of Media 150 g PuO2		0.00411	0.00205	0.00137	0.00103	0.00082	0.00068	0.00059	0.00051	Thickness of PuO2 Layer Both Sides of Media 150 g PuO2		0.00046	0.00041	0.00037	0.00036
Gram Density of PuO2		1	2	3	4	5	6	7	8	Gram Density of PuO2		9	10	11	11.46
Coordinates															
200 g Single Layer +x from Media of +x = 0.0381		0.04906	0.04358	0.04175	0.04084	0.04029	0.03993	0.03967	0.03947	200 g Single Layer +x from Media of +x = 0.0381		0.03932	0.03920	0.03910	0.03906
150 g Single Layer +x from Media of +x = 0.0381		0.04632	0.04221	0.04084	0.04015	0.03974	0.03947	0.03927	0.03913	150 g Single Layer +x from Media of +x = 0.0381		0.03901	0.03892	0.03885	0.03882
200 g Double Layer +x from Media of +x = 0.0		0.00548	0.00274	0.00183	0.00137	0.00110	0.00091	0.00078	0.00068	200 g Double Layer +x from Media of +x = 0.0		0.00061	0.00055	0.00050	0.00048
200 g Double Layer +x of Media		0.04358	0.04084	0.03993	0.03947	0.03920	0.03901	0.03888	0.03878	200 g Double Layer +x of Media		0.03871	0.03865	0.03860	0.03858
200 g Double Layer +x from Media of +x		0.04906	0.04358	0.04175	0.04084	0.04029	0.03993	0.03967	0.03947	200 g Double Layer +x from Media of +x		0.03932	0.03920	0.03910	0.03906
200 g Double Layer +x of water channel for +x PuO2		0.51983	0.51709	0.51618	0.51572	0.51545	0.51526	0.51513	0.51503	200 g Double Layer +x of water channel for +x PuO2		0.51496	0.51490	0.51485	0.51483
150 g Double Layer +x from Media of +x = 0.0		0.00411	0.00205	0.00137	0.00103	0.00082	0.00068	0.00059	0.00051	150 g Double Layer +x from Media of +x = 0.0		0.00046	0.00041	0.00037	0.00036
150 g Double Layer +x of Media		0.04221	0.04015	0.03947	0.03913	0.03892	0.03878	0.03869	0.03861	150 g Double Layer +x of Media		0.03856	0.03851	0.03847	0.03846
150 g Double Layer +x from Media of +x		0.04632	0.04221	0.04084	0.04015	0.03974	0.03947	0.03927	0.03913	150 g Double Layer +x from Media of +x		0.03901	0.03892	0.03885	0.03882
150 g Double Layer +x of water channel for +x PuO2		0.51846	0.51640	0.51572	0.51538	0.51517	0.51503	0.51494	0.51486	150 g Double Layer +x of water channel for +x PuO2		0.51481	0.51476	0.51472	0.51471

Table A-3. Calculational data for an overloaded 30.5 × 30.5 × 15.2-cm (12 × 12 × 6-in.) filter.

Y length of Filter Media (cm)	26.67							
Z Length of Filter Media (cm)	14.9225							
Area of One Sheet (cm2)	397.983075							
# of Sheets in Filter	52							
Total Area of Filter Media (cm2)	20695.1199							
MA Pu239(95%) Pu240 (5%)	239.1021							
MA Pu239(95%) Pu240 (5%)O2	271.1009							
Density of PuO2 (g/cm3)	11.46							
Grams of Pu (g)	200	150						
Grams of PuO2 (g)	226.77	170.07						
Gram Density of PuO2	2							
Mass of PuO2 (g)	226.77							
Volume of PuO2 (cm3)	113.38							
N ²³⁹	4.2205E-03							
N ²⁴⁰	2.2213E-04							
N ^O	8.8853E-03							
N ^H	5.5088E-02							
N ^O	2.7544E-02							
N ^{O Tot}	3.6429E-02							
N ^{Tot}	9.59596E-02							
H/Pu Ratio	13.05							
Mass of Pu (g)	200.00	300.00	400.00	500.00	600.00	700.00	800.00	900.00
Mass of PuO ₂ (g)	226.77	340.15	453.53	566.91	680.30	793.68	907.06	1020.45
Volume of PuO ₂ (cm ³)	113.38	170.07	226.77	283.46	340.15	396.84	453.53	510.22
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.00548	0.00822	0.01096	0.01370	0.01644	0.01918	0.02191	0.02465
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.00274	0.00411	0.00548	0.00685	0.00822	0.00959	0.01096	0.01233
200 g Single Layer +x from Media of +x = 0.0381	0.04358	0.04632	0.04906	0.05180	0.05454	0.05728	0.06001	0.06275
Mass of Pu (g)	1000.00	1100.00	1200.00	1300.00	1400.00	1500.00		
Mass of PuO ₂ (g)	1133.83	1247.21	1360.59	1473.98	1587.36	1700.74		
Volume of PuO ₂ (cm ³)	566.91	623.61	680.30	736.99	793.68	850.37		
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.02739	0.03013	0.03287	0.03561	0.03835	0.04109		
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.01370	0.01507	0.01644	0.01781	0.01918	0.02055		
200 g Single Layer +x from Media of +x = 0.0381	0.06549	0.06823	0.07097	0.07371	0.07645	0.07919		

Table A-5. Computational data for a 50-g (1.8-oz) and a 10-g (0.35-oz) 20.3 × 20.3 × 15-cm (8 × 8 × 5-7/8-in.) filter.

09/24/2001 10:30													
Z length of Filter Media (cm)	14.9225												
Y Length of Filter Media (cm)	16.51												
Area of One Sheet (cm2)	246.370475												
# of Sheets in Filter	32												
Total Area of Filter Media (cm2)	7883.8552												
MA Pu239(95%) Pu240 (5%)	239.1021												
MA Pu239	239.0521												
MA Pu240	240.0538												
MA Pu239(95%) Pu240 (5%)O2	271.1009												
Density of PuO2 (g/cm3)	11.46												
Grams of Pu (g)	50 10												
Grams of PuO2 (g)	56.69 11.34												
Gram Density of PuO2	1	2	3	4	5	6	7	8	Gram Density of PuO2	9	10	11	11.46
Mass of PuO2 (g)	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	Mass of PuO2 (g)	56.69	56.69	56.69	56.69
Volume of PuO2 (cm3)	56.69	28.35	18.90	14.17	11.34	9.45	8.10	7.09	Volume of PuO2 (cm3)	6.30	5.67	5.15	4.95
N ²³⁹	2.1107E-03	4.2214E-03	6.3321E-03	8.4428E-03	1.0553E-02	1.2664E-02	1.4775E-02	1.6886E-02	N ²³⁹	1.8996E-02	2.1107E-02	2.3218E-02	2.4188E-02
N ²⁴⁰	1.1063E-04	2.2125E-04	3.3188E-04	4.4250E-04	5.5313E-04	6.6375E-04	7.7438E-04	8.8500E-04	N ²⁴⁰	9.9563E-04	1.1063E-03	1.2169E-03	1.2678E-03
N ^O	4.4426E-03	8.8853E-03	1.3328E-02	1.7771E-02	2.2213E-02	2.6656E-02	3.1098E-02	3.5541E-02	N ^O	3.9984E-02	4.4426E-02	4.8869E-02	5.0913E-02
N ^H	6.0911E-02	5.5088E-02	4.9265E-02	4.3441E-02	3.7618E-02	3.1795E-02	2.5972E-02	2.0148E-02	N ^H	1.4325E-02	8.5019E-03	2.6787E-03	0.0000E+00
N ^O	3.0456E-02	2.7544E-02	2.4632E-02	2.1721E-02	1.8809E-02	1.5897E-02	1.2986E-02	1.0074E-02	N ^O	7.1626E-03	4.2510E-03	1.3393E-03	0.0000E+00
N ^{O Tot}	3.4898E-02	3.6429E-02	3.7960E-02	3.9491E-02	4.1022E-02	4.2553E-02	4.4084E-02	4.5615E-02	N ^{O Tot}	4.7146E-02	4.8677E-02	5.0208E-02	5.0913E-02
N ^{Tot}	9.8031E-02	9.5960E-02	9.3889E-02	9.1818E-02	8.9747E-02	8.7676E-02	8.5605E-02	8.3534E-02	N ^{Tot}	8.1463E-02	7.9392E-02	7.7321E-02	7.6369E-02
H/Pu Ratio	28.86	13.05	7.78	5.15	3.56	2.51	1.76	1.19		0.75	0.40	0.12	0.00
Mass of PuO2 (g)	11.34	11.34	11.34	11.34	11.34	11.34	11.34	11.34	Mass of PuO2 (g)	11.34	11.34	11.34	11.34
Volume of PuO2 (cm3)	11.34	5.67	3.78	2.83	2.27	1.89	1.62	1.42	Volume of PuO2 (cm3)	1.26	1.13	1.03	0.99
Thickness of PuO2 Layer Single Side of Media 50g PuO2	0.00719	0.00360	0.00240	0.00180	0.00144	0.00120	0.00103	0.00090	Thickness of PuO2 Layer Single Side of Media 50 g PuO2	0.00080	0.00072	0.00065	0.00063
Thickness of PuO2 Layer Both Sides of Media 50 g PuO2	0.00360	0.00180	0.00120	0.00090	0.00072	0.00060	0.00051	0.00045	Thickness of PuO2 Layer Both Sides of Media 50 g PuO2	0.00040	0.00036	0.00033	0.00031
Thickness of PuO2 Layer Single Side of Media 10 g PuO2	0.00144	0.00072	0.00048	0.00036	0.00029	0.00024	0.00021	0.00018	Thickness of PuO2 Layer Single Side of Media 10 g PuO2	0.00016	0.00014	0.00013	0.00013
Thickness of PuO2 Layer Both Sides of Media 10 g PuO2	0.00072	0.00036	0.00024	0.00018	0.00014	0.00012	0.00010	0.00009	Thickness of PuO2 Layer Both Sides of Media 10 g PuO2	0.00008	0.00007	0.00007	0.00006
Gram Density of PuO2	1	2	3	4	5	6	7	8	Gram Density of PuO2	9	10	11	11.46
Coordinates	Coordinates								Coordinates				
50 g Single Layer +x from Media of +x = 0.0381	0.04529	0.04170	0.04050	0.03990	0.03954	0.03930	0.03913	0.03900	50 g Single Layer +x from Media of +x = 0.0381	0.03890	0.03882	0.03875	0.03873
10 g Single Layer +x from Media of +x = 0.0381	0.03954	0.03882	0.03858	0.03846	0.03839	0.03834	0.03831	0.03828	10 g Single Layer +x from Media of +x = 0.0381	0.03826	0.03824	0.03823	0.03823
50 g Double Layer +x from Media of +x = 0.0	0.00360	0.00180	0.00120	0.00090	0.00072	0.00060	0.00051	0.00045	50 g Double Layer +x from Media of +x = 0.0	0.00040	0.00036	0.00033	0.00031
50 g Double Layer +x of Media	0.04170	0.03990	0.03930	0.03900	0.03882	0.03870	0.03861	0.03855	50 g Double Layer +x of Media	0.03850	0.03846	0.03843	0.03841
50 g Double Layer +x from Media of +x	0.04529	0.04170	0.04050	0.03990	0.03954	0.03930	0.03913	0.03900	50 g Double Layer +x from Media of +x	0.03890	0.03882	0.03875	0.03873
50 g Double Layer +x of water channel for +x PuO2	0.51795	0.51615	0.51555	0.51525	0.51507	0.51495	0.51486	0.51480	50 g Double Layer +x of water channel for +x PuO2	0.51475	0.51471	0.51468	0.51466
10 g Double Layer +x from Media of +x = 0.0	0.00072	0.00036	0.00024	0.00018	0.00014	0.00012	0.00010	0.00009	10 g Double Layer +x from Media of +x = 0.0	0.00008	0.00007	0.00007	0.00006
10 g Double Layer +x of Media	0.03882	0.03846	0.03834	0.03828	0.03824	0.03822	0.03820	0.03819	10 g Double Layer +x of Media	0.03818	0.03817	0.03817	0.03816
10 g Double Layer +x from Media of +x	0.03954	0.03882	0.03858	0.03846	0.03839	0.03834	0.03831	0.03828	10 g Double Layer +x from Media of +x	0.03826	0.03824	0.03823	0.03823
10 g Double Layer +x of water channel for +x PuO2	0.51507	0.51471	0.51459	0.51453	0.51449	0.51447	0.51445	0.51444	10 g Double Layer +x of water channel for +x PuO2	0.51443	0.51442	0.51442	0.51441

Table A-7. Graphite calculations.								
²³⁹ Pu(95%) ²⁴⁰ Pu(5%) O ₂ -Graphite Mixture								
Density of Graphite (g/cm ³)	2.25							
M _A Pu ²³⁹	239.0521							
M _A Pu ²⁴⁰	240.0538							
M _A Pu ²³⁹ (95%) Pu ²⁴⁰ (5%)	239.1021							
M _A Pu ²³⁹ (95%) Pu ²⁴⁰ (5%)O ₂	271.1009							
Density of PuO ₂ (g/cm ³)	11.46							
Grams of Pu (g)	1500	200	400	600	800	1000		
Grams of PuO ₂ (g)	1700.74	226.77	453.53	680.30	907.06	1133.83		
Volume of PuO ₂ (cm ³)	148.41	19.79	39.58	59.36	79.15	98.94		
M _A Carbon Graphite	12.011							
N ^C Pure Graphite	1.1281E-01							
0% Volume Fraction H ₂ O								
Not Ignoring the volume occupied by the PuO ₂								
N ^C	1.1273E-01							
Inside Radius of 55 Gal Drum (cm)	28.57							
Inside Hieght of 55 Gal Drum (cm)	85.09							
Vol of 55 Gal Drum (cm3)	218197.0512							
Mass of C in Drum (g)	490943.3653							
Radius of Graphite Sphere (cm)	37.3467							
1000 g Pu case								
Radius of PuO ₂ in Graphite (cm)	5.0	10.0	15.0	20.0	25.0	30.0	35.0	37.3467
Vol of PuO ₂ - C at Radius (cm ³)	523.5988	4188.7902	14137.1669	33510.3216	65449.8469	113097.3355	179594.3800	218194.6815
N ²³⁹	4.5706E-03	5.7132E-04	1.6928E-04	7.1416E-05	3.6565E-05	2.1160E-05	1.3325E-05	1.0968E-05
N ²⁴⁰	2.3955E-04	2.9944E-05	8.8724E-06	3.7430E-06	1.9164E-06	1.1090E-06	6.9841E-07	5.7485E-07
N ^O	9.6203E-03	1.2025E-03	3.5631E-04	1.5032E-04	7.6962E-05	4.4538E-05	2.8048E-05	2.3086E-05
N ^C	9.1493E-02	1.1014E-01	1.1202E-01	1.1248E-01	1.1264E-01	1.1271E-01	1.1275E-01	1.1276E-01
N ^{Tot}	1.059234E-01	1.119484E-01	1.125541E-01	1.127015E-01	1.127540E-01	1.127772E-01	1.127890E-01	1.127926E-01
Density of PuO ₂ in Graphite (g/cm ³)	2.16545	0.27068	0.08020	0.03384	0.01732	0.01003	0.00631	0.00520

Table A-7. (continued)

Graphite-H ₂ O and PuO ₂ Cases							
1000 g Pu							
Void Fraction in Graphite System	10%	20%	30%	40%	50%	60%	70%
Volume of Graphite System (cm ³)	242441.168	272746.314	311710.0732	363661.752	436394.1024	545492.6281	727323.5041
Radius of System (cm)	38.6803	40.2291	42.0602	44.2779	47.0522	50.6854	55.7865
N ^C	1.0153E-01	9.0247E-02	7.8966E-02	6.7685E-02	5.6405E-02	4.5124E-02	3.3843E-02
N ²³⁹	1.1192E-05	9.9486E-06	8.7050E-06	7.4614E-06	6.2179E-06	4.9743E-06	3.7307E-06
N ²⁴⁰	5.8660E-07	5.2142E-07	4.5625E-07	3.9107E-07	3.2589E-07	2.6071E-07	1.9553E-07
N ^{O PuO2}	2.35575E-05	2.094E-05	1.83225E-05	1.5705E-05	1.30875E-05	1.047E-05	7.85249E-06
N ^H	6.6734E-03	1.3347E-02	2.0020E-02	2.6694E-02	3.3367E-02	4.0041E-02	4.6714E-02
N ^{O H2O}	3.3367E-03	6.6734E-03	1.0010E-02	1.3347E-02	1.6684E-02	2.0020E-02	2.3357E-02
N ^{O Tot}	3.3603E-03	6.6944E-03	1.0028E-02	1.3363E-02	1.6697E-02	2.0031E-02	2.3365E-02
N ^{Tot}	1.115737E-01	1.102990E-01	1.090243E-01	1.077496E-01	1.064749E-01	1.052002E-01	1.039255E-01
H/Pu Ratio	596.26	1341.59	2299.86	3577.56	5366.35	8049.52	12521.48
C/Pu Ratio	9071.39	9071.39	9071.39	9071.39	9071.39	9071.39	9071.39
Graphite-H ₂ O and PuO ₂ Cases in Drums							
1000 g Pu Cases							
Void Fraction in Graphite System	10%	20%	30%	40%			
Volume of Graphite System (cm ³)	196377.3461	174557.641	152737.9359	130918.2307			
N ^C	1.0153E-01	9.0247E-02	7.8966E-02	6.7685E-02			
N ²³⁹	1.24357E-05	1.24357E-05	1.24357E-05	1.24357E-05			
N ²⁴⁰	6.5178E-07	6.5178E-07	6.5178E-07	6.5178E-07			
N ^{O PuO2}	2.30855E-05	2.30855E-05	2.30855E-05	2.30855E-05			
N ^H	6.6734E-03	1.3347E-02	2.0020E-02	2.6694E-02			
N ^{O H2O}	3.3367E-03	6.6734E-03	1.0010E-02	1.3347E-02			
N ^{O Tot}	3.3598E-03	6.6965E-03	1.0033E-02	1.3370E-02			
N ^{Tot}	1.1157450E-01	1.1030374E-01	1.0903298E-01	1.0776222E-01			
H/Pu Ratio	536.63	1073.27	1609.90	2146.54			
C/Pu Ratio	8164.25	7257.11	6349.97	5442.83			

Table A-8. Calculations for magnesium oxide.

²³⁹ Pu(95%) ²⁴⁰ Pu(5%) O ₂ -MgO Mixture								
Density of MgO (g/cm ³)	3.58							
M _A Pu ²³⁹ (95%) Pu ²⁴⁰ (5%)	239.1021							
M _A Pu ²³⁹ (95%) Pu ²⁴⁰ (5%)O ₂	271.1009							
Density of PuO ₂ (g/cm ³)	11.46							
Grams of Pu (g)	1500							
Grams of PuO ₂ (g)	1700.74							
Volume of PuO ₂ (cm ³)	148.41							
M _A MgO	40.3044							
N ^{Mg} MgO	5.3490E-02							
N ^O MgO	5.3490E-02							
0% Volume Fraction H ₂ O								
Not Ignoring the volume occupied by the PuO ₂								
Inside Radius of 55 Gal Drum (cm)	28.57							
Inside Hieght of 55 Gal Drum (cm)	85.09							
Vol of 55 Gal Drum (cm3)	218197.0512							
Mass of MgO in Drum (g)	781145.4434							
Radius of MgO Sphere (cm)	37.3467							
Radius of PuO ₂ in MgO (cm)	5.0	10.0	15.0	20.0	25.0	30.0	35.0	37.3467
Vol of PuO ₂ at Radius (cm ³)	523.5988	4188.7902	14137.1669	33510.3216	65449.8469	113097.3355	179594.3800	218194.6815
N ²³⁹	6.8545E-03	8.5681E-04	2.5387E-04	1.0710E-04	5.4836E-05	3.1734E-05	1.9984E-05	1.6449E-05
N ²⁴⁰	3.6076E-04	4.5095E-05	1.3362E-05	5.6369E-06	2.8861E-06	1.6702E-06	1.0518E-06	8.6571E-07
N ^O PuO ₂	1.4430E-02	1.8038E-03	5.3446E-04	2.2548E-04	1.1544E-04	6.6808E-05	4.2071E-05	3.4629E-05
N ^{Mg}	3.8329E-02	5.1595E-02	5.2928E-02	5.3253E-02	5.3369E-02	5.3420E-02	5.3446E-02	5.3453E-02
N ^O	3.8329E-02	5.1595E-02	5.2928E-02	5.3253E-02	5.3369E-02	5.3420E-02	5.3446E-02	5.3453E-02
N ^{OTot}	5.2759E-02	5.3399E-02	5.3463E-02	5.3478E-02	5.3484E-02	5.3486E-02	5.3488E-02	5.3488E-02
N ^{Tot}	9.830343E-02	1.058952E-01	1.066583E-01	1.068441E-01	1.069103E-01	1.069395E-01	1.069544E-01	1.069589E-01
Density of PuO ₂ in MgO (g/cm ³)	3.24818	0.40602	0.12030	0.05075	0.02599	0.01504	0.00947	0.00779

Table A-8. (continued)

MgO-H ₂ O and PuO ₂ Cases							
Void Fraction in MgO System	10%	20%	30%	40%	50%	60%	70%
Volume of MgO System (cm ³)	242441.168	272746.314	311710.0732	363661.752	436394.1024	545492.6281	727323.5041
Radius of System (cm)	38.6803	40.2291	42.0602	44.2779	47.0522	50.6854	55.7865
N ^{Mg}	4.8141E-02	4.2792E-02	3.7443E-02	3.2094E-02	2.6745E-02	2.1396E-02	1.6047E-02
N ^O	4.8141E-02	4.2792E-02	3.7443E-02	3.2094E-02	2.6745E-02	2.1396E-02	1.6047E-02
N ²³⁹	1.4804E-05	1.3159E-05	1.1514E-05	9.8690E-06	8.2242E-06	6.5794E-06	4.9345E-06
N ²⁴⁰	7.7913E-07	6.9256E-07	6.0599E-07	5.1942E-07	4.3285E-07	3.4628E-07	2.5971E-07
N ^{O PuO2}	3.11654E-05	2.77025E-05	2.42397E-05	2.07769E-05	1.73141E-05	1.38513E-05	1.03885E-05
N ^H	6.6734E-03	1.3347E-02	2.0020E-02	2.6694E-02	3.3367E-02	4.0041E-02	4.6714E-02
N ^{O H2O}	3.3367E-03	6.6734E-03	1.0010E-02	1.3347E-02	1.6684E-02	2.0020E-02	2.3357E-02
N ^{O Tot}	5.1509E-02	4.9493E-02	4.7477E-02	4.5462E-02	4.3446E-02	4.1430E-02	3.9414E-02
N ^{Tot}	1.063386E-01	1.056456E-01	1.049526E-01	1.042596E-01	1.035666E-01	1.028735E-01	1.021805E-01
H/Pu Ratio	450.80	1014.30	1738.80	2704.80	4057.19	6085.79	9466.79
MgO/Pu Ratio	3251.98	3251.98	3251.98	3251.98	3251.98	3251.98	3251.98

Appendix B

Subsurface Disposal Area Soil Information

Appendix B

Subsurface Disposal Area Soil Information

The tables in this appendix show the soil composition and input parameters used in the computational models.

Table B-1. Analysis of soil sample from the spreading areas ^aat the Idaho National Engineering and Environmental Laboratory.

Oxide	Composition (wt%)
SiO ₂	62.60
Al ₂ O ₃	11.85
Fe ₂ O ₃	4.25
CaO	3.68
K ₂ O	2.99
MgO	1.72
Na ₂ O	1.37
TiO ₂	0.68
MnO ₂	0.10
BaO	0.09
ZrO ₂	0.05
B ₂ O ₃	0.05
NiO	0.04
SrO	0.02
Cr ₂ O ₃	0.02
Total oxide	89.51
Moisture	7.5

^a. Data were taken from Callow et al. (1991).

Table B-2. Normalized soil sample from the spreading areas at the Idaho National Engineering and Environmental Laboratory.

Oxide	Composition (wt%)
SiO ₂	69.936
Al ₂ O ₃	13.239
Fe ₂ O ₃	4.748
CaO	4.111
K ₂ O	3.340
MgO	1.922
Na ₂ O	1.531
TiO ₂	0.760
MnO ₂	0.112
BaO	0.101
ZrO ₂	0.056
B ₂ O ₃	0.056
NiO	0.044
SrO	0.022
Cr ₂ O ₃	0.022
Total oxide	100.0

Table B-3. Compositions of soil from the Subsurface Disposal Area at the Idaho National Engineering and Environmental Laboratory.

Description	Element	Atoms/barn-cm
Wet soil	Si	1.0034E-02
	Al	2.2387E-03
	Fe	5.1263E-04
	Ca	6.3198E-04
	K	6.1135E-04
	Mg	4.1109E-04
	Na	4.2591E-04
	Ti	8.2025E-05
	Mn	1.1108E-05
	B-11	1.3781E-05
	H	2.6742E-02
	O	3.9335E-02
Dry soil	Si	1.0034E-02
	Al	2.2387E-03
	Fe	5.1263E-04
	Ca	6.3198E-04
	K	6.1135E-04
	Mg	4.1109E-04
	Na	4.2591E-04
	Ti	8.2025E-05
	Mn	1.1108E-05
	B-11	1.3781E-05
	O	2.5964E-02

Table B-4. Number densities used for cellulose ($\text{C}_6\text{H}_{10}\text{O}_5$ $\rho_{\text{dens}} = 1.45 \text{ g/cm}^3$) material in the MCNP (RSIC 1997) code models.

Element	Nuclide Identification	Number Density (atoms/bn-cm)
Carbon	6012.50c	3.2310-02
Hydrogen	1001.50c	5.3851-02
Oxygen	8016.50c	2.6925-02

B.1 REFERENCE

- Callow, R. A., L. E. Thompson, J. R. Weidner, C. A. Loehr, B. P. McGrail, and S. O. Bates, 1991, *In Situ Vittrification Application to Buried Waste Final Report of Intermediate Field Tests and Idaho National Engineering Laboratory*, EGG WTD-9807, Idaho National Engineering and Environmental Laboratory, EG&G Idaho, Idaho Falls, Idaho.
- RSIC, 1997, "MCNP4-A General Monte Carlo N-Particle Transport Code, Version 4B," CCC-660/MCNP4B2, Radiation Shielding Information Center (contributed by Los Alamos National Laboratory), Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Appendix C

**Sample of Monte Carlo N-Particle Transport Code
Input Listings**

Appendix C

Sample of Monte Carlo N-Particle Transport Code Input Listings

This appendix contains examples of the Monte Carlo N-Particle Transport Code input listings for various computational models used in this criticality safety study of the Subsurface Disposal Area for Operable Unit 7-13/14.

Case 8x8x5_13a:

2 x 1 x 2 array of 8 x 8 x 5 7/8-in glovebox high-efficiency particulate air (HEPA) filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters with full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_13a - Subsurface Disposal Area (SDA) Arrays of 8x8x5 filters

```

c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modelled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c Cards 1-6 are the 200 g Pu loaded filters
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -50 u=1 $ Layer of PuO2 & H2O
3 3 -1.0 +50 u=1 $ Water Between Fiber Media Sheets
4 0 +1 -3
    lat=1 u=2
    fill=-50:50 0:0 0:0
    1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
    fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
    fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9 0 -14 +15 -16 +17 -18 +19
    fill=4 u=5 lat=1 $ Single Filter in Soil
10 0 -30 +31 -32 +33 -34 +35
    fill=5 u=6
11 5 8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0 -400 fill=6
13 0 +400 $ZLOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.05248 $ Thickness of PuO2 and H2O
3 px 0.51435 $ 0.1875" Gap Due to 3/16" Mandrel
4 px 8.2550 $ +x Filter Media
5 px -8.2550 $ -x Filter Media
6 py 8.2550 $ +y Filter Media
7 py -8.2550 $ -y Filter Media

```

```

8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 10.1600 $ +x Plywood
11 px -10.1600 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood
14 px 10.66 $ +x Soil
15 px -10.66 $ -x Soil
16 py 10.66 $ +y Soil
17 py -10.66 $ -y Soil
18 pz 7.96125 $ +z Filter
19 pz -7.96125 $ -z Filter
30 px 31.9799 $ +x Boundary of Array
31 px -10.6599 $ -x Boundary of Array
32 py 10.6599 $ +y Boundary of Array
33 py -10.6599 $ -y Boundary of Array
34 pz 23.8836 $ +z Boundary of Array
35 pz -7.9611 $ -z Boundary of Array
400 so 200

```

```

mode n
imp:n 1 11r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1
c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4 94239.55c 4.2214-03 94240.50c 2.2125-04
    1001.50c 5.5088-02 8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print

```

Case12x12x6_2a:

2 x 1 x 2 array of 12 x 12 x 6-in.glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – full reflection around array with saturated Subsurface Disposal Area soil

Case 12x12x6_2b - Subsurface Disposal Area (SDA) Arrays of 12x12x6 Filters

```

c
c 200 g 239Pu per filter
c Soil reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modelled inside water saturated soil
c
c 1.0 cm spacing between filters in each array
c
c PuO2 Modelled as a layer of PuO2 (3 g/cm3) and H2O (0.7382 g/cm3) on each of the
c   filter media cellulose sheets
c
c PuO2 Modelled as 95% Pu239 and 5% Pu240
c
c Cards 1-7 are the 200 g Pu loaded filters
c
1  1  1.13086-01 -2      u=1 $ Cellulose Media
2  4  9.38887-02 +2 -50   u=1 $ Layer of PuO2
3  3  -1.0      +50      u=1 $ Water Between Fiber Media Sheets
4  0      +1 -3
    lat=1 u=2
    fill=-50:50 0:0 0:0
    1 100r
5  0      -4 +5 -6 +7    $ Total Filter Media, Void And Pu
    fill=2 u=3
6  2  -1.45      (+4:-5:+6:-7) u=3 $ Plywood Frame
7  0      -10 +11 -12 +13 -8 +9
    fill=3 u=4
8  5  8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9  0      -14 +15 -16 +17 -18 +19
    fill=4 u=5 lat=1    $ Single Filter in Soil
10 0      -30 +31 -32 +33 -34 +35
    fill=5 u=6
11 5  8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0      -400 fill=6
13 0      +400          $ZLOW

1  px  0.0
2  px  0.0381    $ +x thickness of media
50 px  0.04175   $ Thickness of PuO2 and H2O
3  px  0.51435   $ 0.1875" Gap Due to 3/16" Mandrel
4  px  13.3350   $ +x Filter Media
5  px -13.3350   $ -x Filter Media
6  py  13.3350   $ +y Filter Media
7  py -13.3350   $ -y Filter Media
8  pz  7.46125   $ +z Filter
9  pz -7.46125   $ -z Filter
10 px  15.24     $ +x Plywood
11 px -15.24     $ -x Plywood
12 py  15.24     $ +y Plywood
13 py -15.24     $ -y Plywood
14 px  15.74     $ Soil
15 px -15.74     $ Soil
16 py  15.74     $ Soil
17 py -15.74     $ Soil
18 pz  7.96125   $ Soil

```



```

19 pz -7.96125 $ Soil
30 px 47.2199 $ +x Boundary of Array
31 px -15.7399 $ -x Boundary of Array
32 py 15.7399 $ +y Boundary of Array
33 py -15.7399 $ -y Boundary of Array
34 pz 23.7360 $ +z Boundary of Array
35 pz -7.4611 $ -z Boundary of Array
400 so 200

```

```

mode n
imp:n 1 11r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1
c
c PuO2 (3 g/cm3) and H2O (0.7382 g/cm3) In Thin Layer
m4 94239.55c 6.3321-03 94240.50c 3.3188-04
    1001.50c 4.9265-02 8016.50c 3.7960-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.04 0 0
c
print

```

Case 8x8x5_10:

2 x 1 x 2 array of 8 x 8 x5-7/8-in. glovebox HEPA filters – 200 g per filter – 0.0 cm edge-to-edge spacing between filters – full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_10 - Subsurface Disposal Area (SDA) Arrays of 8x8x5 Filters

```

c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modelled in water saturated soil
c 0.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c Cards 1-6 are the 200 g Pu loaded filters
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -50 u=1 $ Layer of PuO2 & H2O
3 3 -1.0 +50 u=1 $ Water Between Fiber Media Sheets
4 0 +1 -3
    lat=1 u=2
    fill=-50:50 0:0 0:0
    1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
    fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
    fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9 0 -14 +15 -16 +17 -18 +19
    fill=4 u=5 lat=1 $ Single Filter in Soil
10 0 -30 +31 -32 +33 -34 +35
    fill=5 u=6
11 5 8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0 -400 fill=6
13 0 +400 $ZLOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.05248 $ Thickness of 200g Pu in PuO2 and H2O
51 px 0.04714 $ Thickness of 150g Pu in PuO2 and H2O
3 px 0.51435 $ 0.1875" Gap Due to 3/16" Mandrel
4 px 8.2550 $ +x Filter Media
5 px -8.2550 $ -x Filter Media
6 py 8.2550 $ +y Filter Media
7 py -8.2550 $ -y Filter Media
8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 10.1600 $ +x Plywood
11 px -10.1600 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood
14 px 10.1602 $ +x Soil
15 px -10.1602 $ -x Soil
16 py 10.1602 $ +y Soil

```

```

17 py -10.1602 $ -y Soil
18 pz 7.4614 $ +z Soil
19 pz -7.4614 $ -z Soil
30 px 30.4805 $ +x Boundary of Array
31 px -10.1601 $ -x Boundary of Array
32 py 10.1601 $ +y Boundary of Array
33 py -10.1601 $ -y Boundary of Array
34 pz 22.3841 $ +z Boundary of Array
35 pz -7.4613 $ -z Boundary of Array
400 so 200

mode n
imp:n 1 11r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1
c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4 94239.55c 4.2214-03 94240.50c 2.2125-04
    1001.50c 5.5088-02 8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print

```

Case 14e:

6 x 6 x 6 array of 8 x 8 x 5-7/8-in.glovebox HEPA filters – 50 g per filter – 1.0 cm edge-to-edge spacing between filters – full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_14e - Subsurface Disposal Area (SDA) Arrays of 8x8x5 Filters

```

c
c 50g Pu per filter
c Soil Reflected
c 6x6x6 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modelled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c Cards 1-6 are the 50 g 239Pu loaded filters
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -50 u=1 $ Layer of PuO2 & H2O
3 3 -1.0 +50 u=1 $ Water Between Fiber Media Sheets
4 0 +1 -3
lat=1 u=2
fill=-50:50 0:0 0:0
1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9 0 -14 +15 -16 +17 -18 +19
fill=4 u=5 lat=1 $ Single Filter in Soil
10 0 -30 +31 -32 +33 -34 +35
fill=5 u=6
11 5 8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0 -400 fill=6
13 0 +400 $ZLOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.04170 $ Thickness of 200g Pu in PuO2 and H2O
3 px 0.51435 $ 0.1875" Gap Due to 3/16" Mandrel
4 px 8.2550 $ +x Filter Media
5 px -8.2550 $ -x Filter Media
6 py 8.2550 $ +y Filter Media
7 py -8.2550 $ -y Filter Media
8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 10.1600 $ +x Plywood
11 px -10.1600 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood
14 px 10.66 $ +x Soil
15 px -10.66 $ -x Soil
16 py 10.66 $ +y Soil
17 py -10.66 $ -y Soil
18 pz 7.96125 $ +z Soil
19 pz -7.96125 $ -z Soil

```

```

30  px  74.6199  $ +x Boundary of Array
31  px -53.2999  $ -x Boundary of Array
32  py  74.6199  $ +y Boundary of Array
33  py -53.2999  $ -y Boundary of Array
34  pz  55.7286  $ +z Boundary of Array
35  pz -39.8061  $ -z Boundary of Array
400 so 300

```

mode n

imp:n 1 11r 0

c

c Cellulose Filter Media

m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02

c

c Plywood Frame

m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02

c

c H2O

m3 1001.50c 2 8016.50c 1

c

c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer

m4 94239.55c 4.2214-03 94240.50c 2.2125-04

1001.50c 5.5088-02 8016.50c 3.6429-02

c

c Saturated Soil in SDA (40% Void Volume Filled w H2O)

m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04

20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04

11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05

5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02

c

kcode 4000 1.0 50 200

c

c Source for Array

ksrc 0.4 0 0

c

print

Case 8x8x5_15c:

2 x 1 x 2 array of 8 x 8 x5-7/8-in. glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – soil and water filling gap space within filters - full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_15c - Subsurface Disposal Area (SDA) Arrays of 8x8x5 Filters

```

c
c 200g Pu per filter
c Soil Reflected
c 2x2x3 Array of Filters - Cellulose to Represent CWS Filters
c Soil with varied water volume fraction (wvf) filling void in each filter
c Filters modelled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c 50% water density in 40% void in soil
c
c Cards 1-7 are the 200 g Pu loaded filters
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -50 u=1 $ Layer of PuO2 & H2O
3 6 6.099297-02 +50 u=1 $ Water Between Fiber Media Sheets
4 0 +1 -3
lat=1 u=2
fill=-50:50 0:0 0:0
1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9 0 -14 +15 -16 +17 -18 +19
fill=4 u=5 lat=1 $ Single Filter in Soil
10 0 -30 +31 -32 +33 -34 +35
fill=5 u=6
11 5 8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0 -400 fill=6
13 0 +400 $ZLOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.05248 $ Thickness of 200g Pu in PuO2 and H2O
51 px 0.04714 $ Thickness of 150g Pu in PuO2 and H2O
3 px 0.51435 $ 0.1875" Gap Due to 3/16" Mandrel
4 px 8.2550 $ +x Filter Media
5 px -8.2550 $ -x Filter Media
6 py 8.2550 $ +y Filter Media
7 py -8.2550 $ -y Filter Media
8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 10.1600 $ +x Plywood
11 px -10.1600 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood
14 px 10.66 $ +x Soil
15 px -10.66 $ -x Soil
16 py 10.66 $ +y Soil

```

```

17 py -10.66 $ -y Soil
18 pz 7.96125 $ +z Filter
19 pz -7.96125 $ -z Filter
30 px 31.9799 $ +x Boundary of Array
31 px -10.6599 $ -x Boundary of Array
32 py 31.9799 $ +y Boundary of Array
33 py -10.6599 $ -y Boundary of Array
34 pz 23.8836 $ +z Boundary of Array
35 pz -23.8836 $ -z Boundary of Array
400 so 200

mode n
imp:n 1 11r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1
c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4 94239.55c 4.2214-03 94240.50c 2.2125-04
    1001.50c 5.5088-02 8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
c Saturated Soil in Filters (50% out of 40% Void Volume Filled w H2O)
m6 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 1.3371-02 8016.50c 3.2649-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print

```

Case 8x8x5_16b:

2 x 1 x 2 array of 8 x 8 x5-7/8 glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – soil and water filling gap space in filters - full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_16b - Subsurface Disposal Area (SDA) Arrays of 8x8x5 Filters

```

c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water with varied soil volume fraction (wvf) filling void in each filter
c
c 20% vol frac soil and 80% vol frac H2O in filters
c
c Filters modelled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c 100% water density in 40% void in soil
c
c Cards 1-7 are the 200 g Pu loaded filters
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -50 u=1 $ Layer of PuO2 & H2O
3 6 9.37267-02 +50 u=1 $ Water Between Fiber Media Sheets
4 0 +1 -3
lat=1 u=2
fill=-50:50 0:0 0:0
1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9 0 -14 +15 -16 +17 -18 +19
fill=4 u=5 lat=1 $ Single Filter in Soil
10 0 -30 +31 -32 +33 -34 +35
fill=5 u=6
11 5 8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0 -400 fill=6
13 0 +400 $ZLOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.05248 $ Thickness of 200g Pu in PuO2 and H2O
51 px 0.04714 $ Thickness of 150g Pu in PuO2 and H2O
3 px 0.51435 $ 0.1875" Gap Due to 3/16" Mandrel
4 px 8.2550 $ +x Filter Media
5 px -8.2550 $ -x Filter Media
6 py 8.2550 $ +y Filter Media
7 py -8.2550 $ -y Filter Media
8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 10.1600 $ +x Plywood
11 px -10.1600 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood

```



```

14 px 10.66 $ +x Soil
15 px -10.66 $ -x Soil
16 py 10.66 $ +y Soil
17 py -10.66 $ -y Soil
18 pz 7.96125 $ +z Filter
19 pz -7.96125 $ -z Filter
30 px 31.9799 $ +x Boundary of Array
31 px -10.6599 $ -x Boundary of Array
32 py 10.6599 $ +y Boundary of Array
33 py -10.6599 $ -y Boundary of Array
34 pz 23.8836 $ +z Boundary of Array
35 pz -7.9611 $ -z Boundary of Array
400 so 200

mode n
imp:n 1 11r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1
c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4 94239.55c 4.2214-03 94240.50c 2.2125-04
    1001.50c 5.5088-02 8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
c Water at 80% density with Soil at 20% density in Filters
m6 14000.50c 3.3447-03 13027.50c 7.4623-04 26000.55c 1.7088-04
    20000.50c 2.1066-04 19000.50c 2.0378-04 12000.50c 1.3703-04
    11023.50c 1.4197-04 22000.50c 2.7342-05 25055.50c 3.7027-06
    5011.56c 4.5937-06 1001.50c 5.3387-02 8016.50c 3.5348-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print

```

Case 8x8x5_17c:

2 x 1 x 2 array of 8 x 8 x5-7/8-in. glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – B-10 included from soil in water in filters - full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_17c - Subsurface Disposal Area (SDA) Arrays of 8x8x5 Filters

```

c
c 200g Pu per filter
c Reflected Array by Water Saturated Soil
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modelled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c B-10 included in water in filter
c 50% of B-10 from soil placed into water solution
c
c Cards 1-6 are the 200 g Pu loaded filters
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -50 u=1 $ Layer of PuO2 & H2O
3 6 1.00282316-01 +50 u=1 $ Water & B10 Between Fiber Media Sheets
4 0 +1 -3
   lat=1 u=2
   fill=-50:50 0:0 0:0
   1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
   fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
   fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9 0 -14 +15 -16 +17 -18 +19
   fill=4 u=5 lat=1 $ Single Filter in Soil
10 0 -30 +31 -32 +33 -34 +35
   fill=5 u=6
11 5 8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0 -400 fill=6
13 0 +400 $ZIOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.05248 $ Thickness of 200g Pu in PuO2 and H2O
51 px 0.04714 $ Thickness of 150g Pu in PuO2 and H2O
3 px 0.51435 $ 0.1875" Gap Due to 3/16" Mandrel
4 px 8.2550 $ +x Filter Media
5 px -8.2550 $ -x Filter Media
6 py 8.2550 $ +y Filter Media
7 py -8.2550 $ -y Filter Media
8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 10.1600 $ +x Plywood
11 px -10.1600 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood
14 px 10.66 $ +x Soil
15 px -10.66 $ -x Soil

```

```

16 py 10.66 $ +y Soil
17 py -10.66 $ -y Soil
18 pz 7.96125 $ +z Filter
19 pz -7.96125 $ -z Filter
30 px 31.9799 $ +x Boundary of Array
31 px -10.6599 $ -x Boundary of Array
32 py 10.6599 $ +y Boundary of Array
33 py -10.6599 $ -y Boundary of Array
34 pz 23.8836 $ +z Boundary of Array
35 pz -7.9611 $ -z Boundary of Array
400 so 200

mode n
imp:n 1 11r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1
c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4 94239.55c 4.2214-03 94240.50c 2.2125-04
    1001.50c 5.5088-02 8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
c H2O and B-10 (50% available in SDA soil)
m6 1001.50c 6.6854-02 8016.50c 3.3427-02 5010.50c 1.3161-06
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print

```

Case 8x8x5_18c:

2 x 1 x 2 array of 8 x 8 x 5-7/8 glovebox HEPA filter– 200 g per filter – 1.0 cm edge-to-edge spacing between filters – gap spacing within filters reduced due to crushing of filter- full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_18c - Subsurface Disposal Area (SDA) Arrays of 8x8x5 Filters

```

c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modelled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c Gap spacing decreased to 25% of normal to account for compression
c
c Cards 1-7 are the 200 g Pu loaded filters
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -50 u=1 $ Layer of PuO2 & H2O
3 3 -1.0 +50 u=1 $ Water Between Fiber Media Sheets
4 0 +1 -3
lat=1 u=2
fill=-50:50 0:0 0:0
1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $ Soil
9 0 -14 +15 -16 +17 -18 +19
fill=4 u=5 lat=1 $ Single Filter in Soil
10 0 -30 +31 -32 +33 -34 +35
fill=5 u=6
11 5 8.1049574-02 (+30:-31:+32:-33:+34:-35) u=6
12 0 -400 fill=6
13 0 +400 $ZIOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.05248 $ Thickness of 200g Pu in PuO2 and H2O
3 px 0.157556 $ 50% of Normal Gap Due Compression
4 px 2.52090 $ +x Filter Media
5 px -2.52090 $ -x Filter Media
6 py 8.2550 $ +y Filter Media
7 py -8.2550 $ -y Filter Media
8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 4.4259 $ +x Plywood
11 px -4.4259 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood
14 px 4.93 $ +x Soil
15 px -4.93 $ -x Soil
16 py 10.66 $ +y Soil

```

```

17 py -10.66 $ -y Soil
18 pz 7.96125 $ +z Filter
19 pz -7.96125 $ -z Filter
30 px 14.7899 $ +x Boundary of Array
31 px -4.9299 $ -x Boundary of Array
32 py 10.6599 $ +y Boundary of Array
33 py -10.6599 $ -y Boundary of Array
34 pz 23.8836 $ +z Boundary of Array
35 pz -7.9611 $ -z Boundary of Array
400 so 200

mode n
imp:n 1 11r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1
c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4 94239.55c 4.2214-03 94240.50c 2.2125-04
    1001.50c 5.5088-02 8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print

```

Case 8x8x5_20a:

2 x 1 x 2 array of 8 x 8 x 5-7/8-in. glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – area over filter sheets that PuO₂ is dispersed is reduced - full reflection around array with saturated Subsurface Disposal Area soil

Case 8x8x5_20a - Subsurface Disposal Area (SDA) Arrays of 8x8x5 Filters

```

c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modelled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c Pu modelled as 95% Pu239 5% Pu240
c
c In this case the PuO2 is spread over a reduced area 75% of total filter area
c thus effectively increasing the thickness of the layer of PuO2
c
c Cards 1-9 are the 200 g Pu loaded filters Top Row
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.5960-02 +2 -55 -50 u=1 $ Layer of PuO2 & H2O
3 3 -1.0 +2 +55 -50 u=1 $ Layer of H2O
4 3 -1.0 +50 u=1 $ Water Between Fiber Media Sheets
5 0 +1 -3
lat=1 u=2
fill=-50:50 0:0 0:0
1 100r
6 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
fill=2 u=3
7 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
8 0 -10 +11 -12 +13 -8 +9
fill=3 u=4
9 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
c
c Cards 10-18 are the 200 g Pu loaded filters Bottom Row
c
10 1 1.13086-01 -2 u=5 $ Cellulose Media
11 4 9.5960-02 +2 +56 -50 u=5 $ Layer of PuO2 & H2O
12 3 -1.0 +2 -56 -50 u=5 $ Layer of H2O
13 3 -1.0 +50 u=5 $ Water Between Fiber Media Sheets
14 0 +1 -3
lat=1 u=6
fill=-50:50 0:0 0:0
5 100r
15 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
fill=6 u=7
16 2 -1.45 (+4:-5:+6:-7) u=7 $ Plywood Frame
17 0 -10 +11 -12 +13 -8 +9
fill=7 u=8
18 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=8 $Soil
19 0 -14 +15 -16 +17 -18 +19
lat=1 u=9
fill=0:1 0:1 -1:1
8 8 4 4
8 8 4 4
8 8 4 4
20 0 -30 +31 -32 +33 -34 +35 fill=9 u=10
21 5 8.1049574-02 +30:-31:+32:-33:+34:-35 u=10

```

```

22 0          -400 fill=10
23 0          +400          $ZIOW

1  px  0.0
2  px  0.0381  $ +x thickness of media
50 px  0.05728  $ Thickness of 200g Pu in PuO2 and H2O
3  px  0.51435  $ 0.1875" Gap Due to 3/16" Mandrel
4  px  8.2550   $ +x Filter Media
5  px -8.2550   $ -x Filter Media
6  py  8.2550   $ +y Filter Media
55 py  4.1275   $ +y plane to restrict area
56 py -4.1275   $ -y plane to restrict area
7  py -8.2550   $ -y Filter Media
8  pz  7.46125  $ +z Filter
9  pz -7.46125  $ -z Filter
10 px  10.1600  $ +x Plywood
11 px -10.1600  $ -x Plywood
12 py  10.1600  $ +y Plywood
13 py -10.1600  $ -y Plywood
14 px  10.66    $ +x Soil
15 px -10.66    $ -x Soil
16 py  10.66    $ +y Soil
17 py -10.66    $ -y Soil
18 pz  7.96125  $ +z Filter
19 pz -7.96125  $ -z Filter
30 px  31.9799  $ +x Boundary of Array
31 px -10.6599  $ -x Boundary of Array
32 py  10.6599  $ +y Boundary of Array
33 py -10.6599  $ -y Boundary of Array
34 pz  23.8836  $ +z Boundary of Array
35 pz -7.9611   $ -z Boundary of Array
400 so 200

mode n
imp:n 1 21r 0
c
c Cellulose Filter Media
m1  6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c Plywood Frame
m2  6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c H2O
m3  1001.50c 2  8016.50c 1
c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4  94239.55c 4.2214-03  94240.50c 2.2125-04
    1001.50c 5.5088-02  8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5  14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
    20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
    11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
    5011.56c 1.3781-05  1001.50c 2.6742-02  8016.50c 3.9335-02
c
kcode 4004 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print

```

Case 12x12x6_3g

Single 12 x 12 x 6-in. glovebox HEPA Filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – filter overloaded with 1,000g of PuO₂ - full reflection around filter with saturated Subsurface Disposal Area soil

Case 12x12x6_3g - Subsurface Disposal Area (SDA) Single Overloaded Filters

```

c
c 900 g Pu in filter
c Single Filters - Cellulose to Represent CWS Filters
c Water filling void in filter
c Filter modelled inside water saturated soil
c
c PuO2 Modelled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c filter media cellulose sheets
c
c PuO2 Modelled as 95% Pu239 and 5% Pu240
c
c Cards 1-7 are the 900 g Pu loaded filter
c
1 1 1.13086-01 -2 u=1 $ Cellulose Media
2 4 9.59596-02 +2 -50 u=1 $ Layer of PuO2
3 3 -1.0 +50 u=1 $ Water Between Fiber Media Sheets
4 0 +1 -3
lat=1 u=2
fill=-50:50 0:0 0:0
1 100r
5 0 -4 +5 -6 +7 $ Total Filter Media, Void And Pu
fill=2 u=3
6 2 -1.45 (+4:-5:+6:-7) u=3 $ Plywood Frame
7 0 -10 +11 -12 +13 -8 +9
fill=3 u=4
8 5 8.1049574-02 (+10:-11:+12:-13:+8:-9) u=4 $Soil
9 0 -400 fill=4
10 0 +400 $ZIOW

1 px 0.0
2 px 0.0381 $ +x thickness of media
50 px 0.06275 $ Thickness of PuO2 and H2O
3 px 0.51435 $ 0.1875" Gap Due to 3/16" Mandrel
4 px 13.3350 $ +x Filter Media
5 px -13.3350 $ -x Filter Media
6 py 13.3350 $ +y Filter Media
7 py -13.3350 $ -y Filter Media
8 pz 7.46125 $ +z Filter
9 pz -7.46125 $ -z Filter
10 px 15.24 $ +x Plywood
11 px -15.24 $ -x Plywood
12 py 15.24 $ +y Plywood
13 py -15.24 $ -y Plywood
400 so 200

mode n
imp:n 1 8r 0
c
c Cellulose Filter Media
m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c Plywood Frame
m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02
c
c H2O
m3 1001.50c 2 8016.50c 1

```



```

c
c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4 94239.55c 4.2214-03 94240.50c 2.2125-04
    1001.50c 5.5088-02 8016.50c 3.6429-02
c
c Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.04 0 0
c
print

```

Case drums_1a

2 x 2 x 2 array of drums – each drum housing a single 8 x 8 x 5-7/8-in. filter containing 200 g PuO₂ per filter – filters offset in drums to increase reactivity – full reflection with saturated Subsurface Disposal Area soil outside array of drums and within remaining void in drums

Case drums_1a - Subsurface Disposal Area (SDA) 55 Gal Drums Containing

c HEPA Filters 8" x 8" x 5 7/8" Filters

c

c 200g Pu per filter

c Soil Reflected

c 2x2x2 Array of Drums - Cellulose to Represent CWS Filters

c Water filling void in each filter

c

c Drums Touching

c

c PuO₂ Modelled as a layer of PuO₂ (2 g/cm³) and H₂O (0.82548 g/cm³) on each of the filter media cellulose sheets

c

c Pu modelled as 95% Pu²³⁹ 5% Pu²⁴⁰

c

c Cards 1-6 are the 200 g Pu loaded filters

c

1 1 1.13086-01 -2 u=1 \$ Cellulose Media

2 4 9.5960-02 +2 -50 u=1 \$ Layer of PuO₂ & H₂O

3 3 -1.0 +50 u=1 \$ Water Between Fiber Media Sheets

4 0 +1 -3

lat=1 u=2

fill=-50:50 0:0 0:0

1 100r

5 0 -4 +5 -6 +7 \$ Total Filter Media, Void And Pu

fill=2 u=3

6 2 -1.45 (+4:-5:+6:-7) u=3 \$ Plywood Frame

7 0 -10 +11 -12 +13 -8 +9 trcl=(16.4 0 35.078)

fill=3 u=4

8 5 8.1049574-02 #7 u=4 \$Soil

9 0 -14 -16 +17

fill=4 u=5 \$ Single Filter in Drum

10 6 -7.92 +14:+16:-17 u=5 \$ Carbon Steel Drum

11 0 -15 -18 +19

fill=5 u=6

12 like 11 but trcl=1 u=6

13 like 11 but trcl=2 u=6

14 like 11 but trcl=3 u=6

15 like 11 but trcl=4 u=6

16 like 11 but trcl=5 u=6

17 like 11 but trcl=6 u=6

18 like 11 but trcl=7 u=6

19 5 8.1049574-02 #11 #12 #13 #14 #15 #16 #17 #18 u=6

20 0 -400 fill=6

21 0 +400 \$ZLOW

1 px 0.0

2 px 0.0381 \$ +x thickness of media

50 px 0.05248 \$ Thickness of PuO₂ and H₂O

3 px 0.51435 \$ 0.1875" Gap Due to 3/16" Mandrel

4 px 8.2550 \$ +x Filter Media

5 px -8.2550 \$ -x Filter Media

6 py 8.2550 \$ +y Filter Media

7 py -8.2550 \$ -y Filter Media

8 pz 7.46125 \$ +z Filter

9 pz -7.46125 \$ -z Filter

```

10 px 10.1600 $ +x Plywood
11 px -10.1600 $ -x Plywood
12 py 10.1600 $ +y Plywood
13 py -10.1600 $ -y Plywood
14 cz 28.575 $ Inside Radius of Drum
15 cz 28.727 $ Outside Radius of Drum
16 pz 42.545 $ +z Inside of Drum
17 pz -42.545 $ -z Inside of Drum
18 pz 42.695 $ +z Outside of Drum
19 pz -42.695 $ -z Outside of Drum
400 so 400

```

mode n

imp:n 1 19r 0

c

c Cellulose Filter Media

m1 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02

c

c Plywood Frame

m2 6012.50c 3.2310-02 1001.50c 5.3851-02 8016.50c 2.6925-02

c

c H2O

m3 1001.50c 2 8016.50c 1

c

c PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer

m4 94239.55c 4.2214-03 94240.50c 2.2125-04

1001.50c 5.5088-02 8016.50c 3.6429-02

c

c Saturated Soil in SDA (40% Void Volume Filled w H2O)

m5 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04

20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04

11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05

5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02

c

c Carbon Steel Drum (Density 7.93 g/cm3)

m6 6012.50c 1

c

c

tr1* 57.5 0 0 180 90 90 90 180 90 90 90 0

tr2* 28.575 49.9 0 90 180 90 0 90 90 90 90 0

tr3* 28.575 -49.9 0 90 0 90 180 90 90 90 90 0

tr4* 0 0 85.4 0 90 90 90 0 90 90 90 180

tr5* 57.5 0 85.4 180 90 90 90 180 90 90 90 180

tr6* 28.575 49.9 85.4 90 180 90 0 90 90 90 90 180

tr7* 28.575 -49.9 85.4 90 0 90 180 90 90 90 90 180

kcode 4000 1.0 50 200

c

c Source for Array

ksrc 16.9 0 41.9

c

print

Case graphite_1h **1,000 g of plutonium combined with dry graphite in spherical form – fully reflected**

Case graphite_1h - Subsurface Disposal Area (SDA) PuO2 in Graphite

c 1000 g Pu from a single drum

c Soil Reflected

c

c PuO2 Modelled as PuO2 dispersed in graphite.

c

c Pu modelled as 95% Pu239 5% Pu240

c

c PuO2 dispsered over a 37.3467 cm radius sphere of graphite

c 0.007 g/cc of PuO2 in volume modelled

c

c

c

1 1 1.127926-01 -2 \$ PuO2 and Graphite

2 3 8.1049574-02 +2 -3 \$ Water saturated soil

3 0 +3 \$ ZIOW

1 so 35.0 \$ PuO2 in Graphite

2 so 37.3467 \$ Graphite

3 so 150.0 \$ Soil (40% vf water saturated)

mode n

imp:n 1 1 0

c

c PuO2 in Graphite

m1 6012.50c 1.1276-01 94239.55c 1.0968-05 94240.50c 5.7485-07
8016.50c 2.3086-05

c

c Graphite

m2 6012.50c 1.12808-02

c

c Saturated Soil in SDA (40% Void Volume Filled w H2O)

m3 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02

c

kcode 4000 1.0 50 200

c

c Source for Array

ksrc 0 0 0

c

print

Case graphite-2b

1,000 g plutonium combined with graphite and water in spherical form – fully reflected

Case graphite_2b - Subsurface Disposal Area (SDA) PuO₂ in Graphite and H₂O

c 1000 g Pu from a single drum

c Soil Reflected

c

c PuO₂ Modelled as PuO₂ dispersed in graphite and water.

c

c Pu modelled as 95% Pu²³⁹ 5% Pu²⁴⁰

c

c PuO₂ dispersed over a 40.23 cm radius sphere of graphite and water

c 20% volume fraction modelled in graphite filled with water

c

c

c

1 1 1.102990-01 -1 \$ PuO₂, H₂O, Graphite

2 3 8.1049574-02 +1 -2 \$ Water saturated soil

3 0 +2 \$ ZIOW

1 so 40.2291 \$ PuO₂ in Graphite

2 so 300.0 \$ Soil (40% vf water saturated)

mode n

imp:n 1 1 0

c

c PuO₂ in Graphite and H₂O

m1 6012.50c 9.0247-02 94239.55c 9.9486-06 94240.50c 5.2142-07

8016.50c 6.6944-03 1001.50c 1.3347-02

c

c Graphite

m2 6012.50c 1.12808-02

c

c Saturated Soil in SDA (40% Void Volume Filled w H₂O)

m3 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04

20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04

11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05

5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02

c

kcode 4000 1.0 50 200

c

c Source for Array

ksrc 0 0 0

c

print

Case graphite_4a1e

Drum containing PuO₂, graphite, and water – full reflection around drum

Case graphite_4a1e - Subsurface Disposal Area (SDA) PuO₂, H₂O & Graphite in Drum

c 1000 g Pu in a single drum

c Soil Reflected

c

c PuO₂ Modelled as PuO₂ dispersed in 80% density graphite.

c Remaining 20% volume fraction filled with water

c

c Pu modelled as 95% Pu²³⁹ 5% Pu²⁴⁰

c

c PuO₂ dispersed over entire volume of drum

c Single overloaded drum

c

c

c

1 1 1.1030220-01 -1 -2 +3 u=1 \$ PuO₂(1000 g Pu), H₂O & Graphite

2 2 -7.82 +1:+2:-3 u=1

3 0 -4 -5 +6 fill=1 u=2

4 3 8.1049574-02 +4:+5:-6 u=2 \$ Water saturated soil

5 0 -13 +14 -15 +16 -17 +18 fill=2 u=3

6 3 8.1049574-02 +13:-14:+15:-16:+17:-18 u=3 \$ Water saturated soil

7 0 -20 +21 -22 +23 -24 +25 fill=3

8 0 +20:-21:+22:-23:+24:-25 \$ ZIOW

1 cz 28.575 \$ Inside radius of drum

2 pz 42.545 \$ Inside height +z

3 pz -42.545 \$ Inside height -z

4 cz 28.727 \$ Outside radius of drum 0.152 cm thick wall

5 pz 42.695 \$ Outside height of drum 0.15 cm thick wall

6 pz -42.695 \$ Outside height of drum 0.15 cm thick wall

7 px 28.73

8 px -28.73

9 py 28.73

10 py -28.73

11 pz 42.70

12 pz -42.70

13 px 28.7299

14 px -28.7299

15 py 28.7299

16 py -28.7299

17 pz 42.6999

18 pz -42.6999

20 px 200

21 px -200

22 py 200

23 py -200

24 pz 250

25 pz -170

mode n

imp:n 1 6r 0

c

c PuO₂, H₂O, 80% Density Graphite (1000 g Pu in single drum)

m1 6012.50c 9.0247-02 94239.55c 1.0968-05 94240.50c 5.7484-07

8016.50c 6.6965-03 1001.50c 1.3347-02

c

c Carbon Steel

m2 6012.50c 1.96E-03 26000.55c 8.390-02

c

c Saturated Soil in SDA (40% Void Volume Filled w H₂O)

```
m3 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
    20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
    11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
    5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0 0 0
c
print
```

Case mgo_1h:

1,500 g PuO₂ and dry MgO in spherical form – fully reflected

Case mgo_1h - Subsurface Disposal Area (SDA) PuO₂ in MgO

c 1500 g Pu from a single drum

c Soil Reflected

c

c PuO₂ Modelled as PuO₂ dispersed in MgO.

c

c Pu modelled as 95% Pu239 5% Pu240

c

c PuO₂ dispersed over a 35.0 cm radius sphere of MgO

c 0.0077 g/cc of PuO₂ in volume modelled

c

c

c

c

1 1 1.069589-01 -1 \$ PuO₂ and MgO

2 3 8.1049574-02 +1 -2 \$ Water saturated soil

3 0 +2 \$ ZIOW

1 so 37.3467 \$ PuO₂ in MgO

2 so 150.0 \$ Soil (40% vf water saturated)

mode n

imp:n 1 1r 0

c

c PuO₂ in MgO

m1 12000.50c 5.3453-02 94239.55c 1.6449-05 94240.50c 8.6571-07
8016.50c 5.3488-02

c

c MgO

m2 12000.50c 5.3453-02 8016.50c 5.3453-02

c

c Saturated Soil in SDA (40% Void Volume Filled w H₂O)

m3 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02

c

kcode 4000 1.0 50 200

c

c Source for Array

ksrc 0 1 0

c

print

Case mgo_2b:

1,500 g PuO₂, MgO, and water in spherical form, fully reflected

Case mgo_2b - Subsurface Disposal Area (SDA) PuO₂ in MgO and H₂O

c 1500 g Pu from a single drum

c Soil Reflected

c

c PuO₂ Modelled as PuO₂ dispersed in MgO and water.

c

c Pu modelled as 95% Pu²³⁹ 5% Pu²⁴⁰

c

c PuO₂ dispersed over a 40.23 cm radius sphere of graphite and water

c 20% volume fraction modelled in MgO filled with water

c

c

c

1 1 1.056456-01 -1 \$ PuO₂, H₂O, MgO

2 3 8.1049574-02 +1 -2 \$ Water saturated soil

3 0 +2 \$ ZIOW

1 so 40.2291 \$ PuO₂ in MgO

2 so 300.0 \$ Soil (40% vf water saturated)

mode n

imp:n 1 1 0

c

c PuO₂ in MgO and H₂O

m1 12000.50c 4.2792-02 94239.55c 1.3159-05 94240.50c 6.9256-07
8016.50c 4.9493-02 1001.50c 1.3347-02

c

c MgO

m2 12000.50c 5.3453-02 8016.50c 5.3453-02

c

c Saturated Soil in SDA (40% Void Volume Filled w H₂O)

m3 14000.50c 1.0034-02 13027.50c 2.2387-03 26000.55c 5.1263-04
20000.50c 6.3198-04 19000.50c 6.1135-04 12000.50c 4.1109-04
11023.50c 4.2591-04 22000.50c 8.2025-05 25055.50c 1.1108-05
5011.56c 1.3781-05 1001.50c 2.6742-02 8016.50c 3.9335-02

c

kcode 4000 1.0 50 200

c

c Source for Array

ksrc 0 0 0

c

print